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AN INVESTIGATION INTO THE APPLICATION OF ELASTIC THEORY TO PREDICT DEFLECTIONS IN FULL-DEPTH ASPHALT PAVEMENTS

by

© DILIP KUMAR DASMOHAPATRA

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled AN INVESTIGATION INTO THE APPLICATION OF ELASTIC THEORY TO PREDICT DEFLECTIONS IN FULL-DEPTH ASPHALT PAVEMENTS submitted by Dilip Kumar Dasmohapatra in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

The purpose of this thesis is to investigate the application of elastic theory to predict deflections in full-depth asphalt pavements. A section on the provincial Highway No. 15 northeast of Edmonton, Alberta, was selected for study. This pavement section was instrumented in two locations to record a) surface deflections and stresses induced at the pavement-subgrade interface, due to the application of standard 18 kip single axle-loads, and b) various temperatures within the pavement structure. The resilient modulus of the subgrade soil was determined in the laboratory in a repeated loading triaxial test apparatus, whereas the stiffness of the asphalt concrete was obtained theoretically using nomographic procedures. These properties of the soil and the asphalt concrete were incorporated in the Chevron 5-layered elastic theory computer program and the surface deflections were computed in an iterative procedure. The computed deflections were compared with the measured field deflections under similar environmental and test conditions.

These comparisons showed that when the subgrade was divided into two layers, one for the compacted subgrade and one for the undisturbed subgrade, the computed and measured deflections were in reasonably close agreement. A design procedure was suggested utilizing the Chevron 5-layered elastic theory computer program. This procedure takes into account the threeway interaction between tolerable deflection, performance and future traffic use as compiled by the Asphalt Institute.

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CHAPTER I

INTRODUCTION

1.1. General

There is a considerable interest on the part of highway engineers to develop a theoretical basis for designing and evaluating asphalt pavements. A number of methods under development involve the application of the theory of elasticity to layered systems as represented by asphalt pavement construction. If it were possible to predict pertinent stress, strain and deflection responses due to wheel-loads by means of theory, a valuable step could be taken in the efficient design and evaluation of pavements and the economical utilization of pavement materials.

Previous investigations in the application of the theory of elasticity to layered systems have been reported in the literature and are discussed in CHAPTER II. These indicate that elastic theory can reasonably be expected to predict deflections and strains due to the application of wheel-loads. This investigation is one of an increasing number of studies designed to verify the available solutions for predicting strain and deflection in layered systems.

1.2. Resilient Modulus

A major problem in solving various mathematical models for stresses and displacements in layered elastic systems by the use of computer programs, is in selecting the appropriate elastic moduli of the various pavement layers from subgrade to surface. For fine-grained cohesive soils commonly used as subgrade materials, the term resilient modulus has been proposed and is widely accepted for this purpose (Seed et al., 1967).

$$M_R = \frac{\sigma_d}{\varepsilon_r} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 1.1$$

in which,

M_R = modulus of resilient deformation in psi;

σ_d = repeatedly applied deviator stress in psi; and

ε_r = resilient axial strain corresponding to a particular number of stress repetitions in inches per inch (recoverable axial strain).

1.3. Pavement Model

A flexible pavement can be considered as consisting of layers of pavement material. Since the particular pavement under study in this investigation is a full-depth asphalt pavement, the materials contained therein are the asphalt concrete and the subgrade soil. The pavement model formulated for structural analysis consisted of a maximum of five layers so that an available elastic theory computer program could be utilized. Each layer can be visualized as consisting of a homogeneous material with very little variation in properties within it.

Various combinations in the number of asphalt concrete layers and the number of subgrade layers in the pavement model were tried, to find a model that would satisfactorily predict surface deflections and stresses induced on the subgrade due to wheel-loads when compared to those measured in the field. The stiffness modulus values assigned to the asphalt concrete were determined by the procedure suggested by McLeod (1969)* based on recovered properties of asphalt concrete and the resilient modulus values assigned to the subgrade soil were obtained from laboratory repeated loading tests on the subgrade soil.

This is very similar to the approach used by Kasianchuk et al. (1969), except that they computed the tensile strain in the asphalt concrete to consider fatigue while surface deflections and vertical stresses in the subgrade were computed in this investigation.

1.4. Objectives of the Thesis

The primary objective of this thesis is to investigate the application of a particular elastic theory layered system analysis procedure to predict pavement responses and to compare these with field measurements. Surface deflections and vertical pressures measured at the pavement-subgrade interface were selected as the main responses for comparison.

Since the "elastic" properties of the pavement layers are required in the analysis, the resilient modulus approach was used to characterize the subgrade soil. The development of suitable laboratory

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* See List of References at end of text.

procedures for compacting and testing specimens at The University of Alberta has been a major phase of the investigation designed to meet this objective.

1.5. Limitations of the Thesis

The prototype pavement used in the study was a full-depth asphalt concrete pavement. Only two sections of this pavement were instrumented and tested during the fall of 1971; consequently data available for comparison were very limited. Hence, the findings of this investigation can only be applied to a full-depth asphalt concrete pavement.

Of the many solutions available for predicting pavement responses in layered systems, only the 5-layered elastic theory computer program developed by the Chevron Research Company was used.

1.6. Organization of the Thesis

The first chapter gives the introduction along with the pavement model, the objectives and the limitations of the thesis. The organization of the thesis is also included.

CHAPTER II reviews the literature on, a) Previous work, b) Repeated loading apparatus, which are important separate entities themselves and must be taken into consideration in this investigation.

The third chapter gives a description of the test project. Along with it is presented the data and test results obtained by the Research Council of Alberta, Highway and River Engineering Division. The data in this chapter are used in subsequent analyses while the deflection test results are used for comparison.

The fourth chapter outlines the testing procedure used, which constitutes a major part of the investigation. The exact operational procedure and the detailed description of various parts are given in APPENDIX A.

The fifth chapter summarizes the test results and a detailed analysis is included.

The sixth chapter gives the practical implications of the findings of this investigation and a design procedure is suggested.

The seventh chapter is a summary of conclusions and recommendations drawn from the literature review and the results of tests and analyses.

The Appendices follow a section on List of References and generally contain routine information on the subgrade material properties, details of test results, details of apparatus and other information of minor importance to warrant its inclusion into the main body of the thesis.

CHAPTER II

REVIEW OF LITERATURE

2.1. General

This chapter reviews the literature necessary for this investigation and is divided into two major sections. The first section deals with previous work in the structural analysis of pavements and materials characterization of pavement components. The second section reviews the literature on various repeated triaxial loading devices.

2.2. Previous Work

The application of elastic theory to the design and evaluation of highway pavements has been widely favoured in the recent years. For more than two decades, a considerable amount of work has been done in this area of research most of which is reported in the Proceedings of the First and Second International Conferences on the Structural Design of Asphalt Pavements published in 1962 and 1967, respectively. A proper description of the behaviour of material under repeated loads, is indispensable for successful application of the elastic theory for layered systems to predict stresses, strains and deflections. The response of road building materials to repeated loading has been extensively studied by Seed and his co-workers at University of California, Berkeley, from

1955 and a summary of their findings has been reported by Seed et al. (1967).

2.2.1. Approach to Structural Analysis

Various multi-layer elastic theories have been proposed in the past, and these have been summarized by Whiffin and Lister (1962). The theories put forward are either two-layer or three-layer elastic theories. Some of these have been presented in tabular and graphical forms by Jones (1962), Peattie (1962), and Ahlvin and Uhlery (1962). With the advent of modern electronic computers, some of the computational difficulties associated with the calculation of stresses, strains and deflections from the appropriate elastic theory for layered systems have been minimized. Thus, so long as appropriate material response characteristics are available, it would appear practicable to use such techniques to study the response of in-service pavements. The Chevron 5-layered elastic theory computer program for calculating stresses, strains and deflections in a pavement has been successfully used by Monismith et al. (1967) and Shifley and Monismith (1968) in predicting pavement deflections.

Various other researchers have demonstrated the applicability of elastic theory to predict stresses and deflections in a pavement. The theory has not only been applied to single-layer systems, but also has been extended to take into account multi-layered systems. A summary of the pertinent information from the previous studies is presented in this section.

Lister and Jones (1967) have examined in some detail the use of circular loaded areas to estimate the stresses existing in the different layers of the structural section. From their analyses they conclude that the assumption of a uniformly loaded circular area defined by the wheel-load divided by the inflation pressure will give results which in other than exceptional circumstances, are in error by less than ± 2 percent when used to calculate interfacial pavement stresses and surface deflections under the whole range of tire-load conditions. They do note, however, that for high length to width ratios for tires which are associated with an overload condition, axial, radial and circumferential stresses will differ from those derived from circular assumption.

Their analysis thus provides some confidence (at least to an engineering approximation) in the use of circular loaded areas, particularly since the Chevron 5-layered elastic theory computer program permits the determination of stresses and strains away from the axis of the load.

Kirk (1967) has attempted to analyse the results of the AASHO road test within the framework of theory. For uncracked sections, he obtained a value of subgrade stress of one psi (based on fall deflection measurements) as being associated with the ability of the pavement sections to carry a large number of load repetitions for axle loads in the range 12 to 30 kips.

Measurements of strains in actual pavements were reported by Gusfeldt and Dempwolff (1967), Klomp and Neisman (1967), and Nijboer and Delcour (1967). While the measured results and results computed by

layered theory are not in precise agreement, all of these investigations demonstrate that layered system elastic theory may be quite useful from an engineering standpoint in assessing the response of pavements to various load conditions.

Coffman (1967) has presented convincing data indicating that laboratory determined moduli for the various components of the pavement structure obtained from sinusoidal loading (complex modulus) can be used within the framework of layered system elastic theory to predict the surface deflection of pavements.

Terrel and Krukar (1970) have used the Chevron 5-layered elastic theory computer program to predict deflections. Their predicted deflections, using layered elastic theory along with material properties determined from dynamic tests on laboratory prepared samples, compared reasonably well with the measured deflections. They have also observed that although the values (like modulus of resilience) are accurately determined, it is difficult to assign appropriate values to these materials in the pavement at various times during the pavement's life. Hence, sampling and testing of the pavement materials obtained at the time of field measurements, would make it substantially easier to establish the effectiveness of this type of analysis and validity of elastic layer theory in general.

Seed et al. (1967) attempted the correlation of surface deflections predicted from repeated-load triaxial tests on representative samples with those measured in repeated plate load tests on a wide range of materials. They obtained reasonable agreement by assuming

that the stresses were those predicted by Boussinesq theory and by taking a relevant soil modulus from triaxial tests carried out at constant radial pressure. Although both of these assumptions are definite over simplifications of the problem, the agreement observed by the authors suggest that within a limited range of test and boundary conditions, the errors are minor.

They have also observed:

> "One of the greatest difficulties is presented by the variation of the resilient modulus of compacted clays with the magnitude of the deviator stress. Because the deviator stress induced in the subgrade due to any wheel-load application varies both vertically and horizontally, the subgrade in general will behave as a material with varying modulus, no matter how homogeneous it might be. Inclusion of such a variation in the elastic theory for layered systems has not been possible to the present time."

From the preceding observation it is evident that the subgrade should be divided into several thin layers so as to have a minimal variation of resilient modulus within a layer.

A number of solutions to boundary value problems of stresses and displacements in earth masses and layered systems are available and these are summarized in an annotated Bibliography (1969). Computer programs for these solutions are also available and Nair (1971) has pointed out:

> "Practicing engineers should note that computer programs are now available for solving layered system problems formulated in accordance with the methodology first outlined by Burmister. The number of layers these programs can handle covers the range of all practical problems. Because these programs have been 'debugged' and are operational, their use in routine design is a practical proposition. These programs provide information on stresses, strains and displacements throughout the pavement system."

One such computer program is a 5-layered elastic theory program developed by the Chevron Research Company, and this has been used in this investigation.

2.2.2. Materials Characterization

a) Subgrade Soil

Seed et al. (1967) have summarized their past investigations into the resilience characteristics of fine-grained cohesive soils (clays) under repeated loads. They have concluded that the factors that influence the resilience of clays under repeated loads are: a) Number of stress applications, b) Age at initial loading, c) Stress intensity, d) Method of compaction, e) Compaction density and water content, and f) Changes in water content and density after compaction. They have also demonstrated that kneading compaction produces laboratory specimens with resilience characteristics similar to those observed in field specimens for the same condition of test.

b) Asphalt Concrete

The stiffness of asphalt concrete must also be incorporated in the multi-layered elastic theory in order to investigate the response of a pavement to repeated loading. There are two ways of determining the stiffness of this and they are:

1) Direct determination of mixture stiffness, in which stiffness is determined from repeated-load flexure or repeated-load compression tests.

2) Indirect method of mixture stiffness determination, in

which stiffness is determined from the recovered properties of asphalt concrete and a nomographic solution.

The indirect method of mixture stiffness determination was used in this thesis, because of its quickness and simplicity. This method yields results that agree fairly closely with the corresponding results obtained from direct determination of mixture stiffness, as shown by Monismith (1966) and McLeod (1969).

Indirect method of stiffness determination. Van der Poel (1954) was the first to suggest the term stiffness to represent the time and temperature dependent characteristics of asphalt concrete. This definition is represented by:

$$S(t,T) = \frac{\sigma}{\varepsilon} \quad .... \quad 2.1$$

where,

S = stiffness (in psi or kg/cm^2);

t = time of loading;

T = temperature;

σ = axial stress (in psi or kg/cm^2); and

ε = axial strain.

From a series of tests on both asphalts and mixtures he demonstrated that the stiffness of a mixture could be determined from a knowledge of the penetration and ring and ball softening point of the asphalt contained therein and the volume concentration of the aggregate. To simplify the stiffness computations, Van der Poel prepared nomographs.

Heukelom and Klomp (1964) have examined this approach in more detail and have suggested the following expression for determining the mixture stiffness using the same characterizing factors developed by Van der Poel.

$$\frac{S_{mix}}{S_{asphalt}} = \left(1 + \frac{2.5}{n} \cdot \frac{C_v}{1 - C_v}\right)^n \quad \ldots \qquad 2.2$$

where,

S_{mix} = mixture stiffness (kg/cm^2);

$S_{asphalt}$ = stiffness of recovered asphalt (kg/cm^2) (from Heukelom and Klomp's nomograph, which is a slight modification of Van der Poel's original nomograph);

C_v = volume concentration of aggregate defined as: $\frac{\text{volume of aggregate}}{\text{volume of (aggregate + asphalt)}}$; and

n = $0.83 \log \frac{4 \times 10^5}{S_{asphalt}}$

Heukelom and Klomp indicate that this expression is valid for mixtures with values for C_v ranging from 0.7 to 0.9 and air void contents of the order of 3 percent, that is, well compacted mixtures.

Van Draat and Sommer (1966) have suggested a correction to be applied to computed stiffness for mixtures with void contents in excess of 3 percent. This correction simply requires using a corrected volume concentration of aggregate in Equation 2.2.

$$C_v' = \frac{C_v}{1 + \Delta V} \quad \ldots\ldots\ldots\ldots\ldots\ldots \qquad 2.3$$

in which,

C_V' = corrected volume concentration of aggregate;

C_V = volume concentration of aggregate defined in Equation 2.2; and

ΔV = difference between actual air void content and the value of 3 percent (expressed in decimal form).

It is suggested however, that the correction is applicable so long as the volume concentration of asphalt C_b exceeds $\frac{2}{3}(1 - C_V)$.

McLeod (1969) has outlined a procedure for the indirect determination of mixture stiffness based on recovered properties of asphalt concrete, and he found reasonable agreement with the measured dynamic modulus.

Finn (1967) has explained the concept of the interchangeability of the time of loading and temperature for a mixture stiffness. He has also demonstrated how a single curve of stiffness versus time for a particular temperature (known as reference temperature) can be obtained for a particular mixture, knowing the stiffness versus time relationship for various temperatures.

The methods suggested by Finn (1967) and McLeod (1969) have been used in this investigation.

2.3. Repeated Loading Apparatus

Highways carry mixed traffic at random intervals, moving at different speeds. Consequently, the pavement is rapidly loaded and unloaded when a vehicle passes over a particular section of it. This

phenomenon is present during the pavement's entire life. Hence, it is desirable to consider repetitive loading when pavement materials are being evaluated.

A repeated loading apparatus should ideally consist of a system that can load and unload samples at a desired frequency with negligible impact effect, and a system for measuring and recording the applied stress and resulting strains. Besides these requirements, the necessity for the measurement of associated parameters dictate other features of the apparatus.

A number of different types of repeated loading apparatus have been developed by various investigators. In order to set up a repeated loading apparatus in the laboratory at The University of Alberta, it was considered necessary to review different features of the various apparatus for applying repeated loads, developed by other investigators. A summary of the essential features of other test equipment is presented in TABLE II-1.

The novel feature of the apparatus developed by Shackel (1970) is a hydromechanical device which can simulate a field stress path. A temperature controlled triaxial cell and a fully automatic data monitoring and acquisition system were incorporated in the equipment.

The installation of a repeated loading triaxial test apparatus in the laboratory at The University of Alberta was under consideration for some time in the past. Progress had been made in the procurement of some parts thereby making the adoption of an apparatus modelled

TABLE II-1

PRINCIPAL EXAMPLES OF REPEATED LOADING EQUIPMENT

Category	Investigators	Stress Path	Pulse Shape	Frequency	Deviator Stress Range σ_D (p.s.i.)	Confining Stress Range σ_3 (p.s.i.)	Specimen Size	Parameters Measured
Pneumatic	Seed and McNeill (1957) Seed and Fead (1959)	B	approximation to square wave	3c/hour to 20c/min	5.0 to 20.0	0 to 14.2	1.4" dia. x 5"	axial strain
	Johnson and Yoder (1963)	B	complex — undefined	40c/min	44.0 to 106.0	30.0 to 40.0	4" dia. x 8"	axial strain vol. strain pore pressure
	Morgan (1966)	B (A)	approximation to square wave (adjustable)	50c/min	20.0 to 50.0	10.0 to 30.0	4" dia. x 8"	axial strain diametral strain
Hydraulic	Dunlap (1965 and 1967)	B	complex — undefined	30c/min	26.0 to 260.0 approx (500 p.s.i. max)	3.0 to 20.0	6" dia. x 12"	axial strain vol. strain
Mechanical	Seed, Chan and Monismith (1955)	B	approximation to square wave	1 to 20 c/min	26.0 to 114.0	14.2	1.4" dia. x 4"	axial strain
	Grainger and Lister (1962)	A or B	similar to prototype	Variable (pulse times from 0.2 to 2 sec	1.8 to 18.0	0 to 8.0	2" dia. x 4"	axial strain pore pressure
	Larew and Leonards (1962)	B	complex — undefined	20 to 22c/min	11 to 208	0 to 20.0	1.4" dia. x 2.8"	axial strain
	Le Tirant and Sarda (1965)	C	(a) sine wave (b) repeated loads	(a) 5 to 7c/sec (b) 50c/min	0.4 to 33.0	0 (unconfined)	5 cm dia. x 10 cm	axial strain
	Yandell (1965)	B	continuous sawtooth wave form	1 to 2 c/min	21.0 to 53.0	5.0 and 40.0	4" dia. x 8"	axial strain vol. strain
Electrical	Pagen and Jagannath (1968)	C	step function	10 to 30 c/min	11.0	0 (unconfined)	1½" dia. x 3"	axial strain diametral strain

After Shackel (1970)

after Seed and Fead (1959) feasible. Features of the apparatus are described in CHAPTER IV, with the details given in APPENDIX A.

2.4. Summary

The review of literature has disclosed that:

1) The elastic theory can reasonably be expected to predict stresses and deflections due to the application of wheel loads.

2) The 5-layered elastic theory computer program developed by the Chevron Research Company is one of the successful computer programs available for solving practical problems in layered systems.

3) The resilient modulus is found to satisfactorily represent the elastic modulus of the subgrade soil for use in these computations.

4) The stiffness of asphalt concrete mixtures can be determined theoretically by the indirect method, according to the procedure suggested by McLeod (1969).

5) An apparatus, such as that developed by Seed and Fead (1959), is suitable for repeated-load triaxial tests on subgrade materials.

CHAPTER III

TEST PROJECT

3.1. Test Project and Site

The development of an elastic design method for pavements has been under investigation for some time under the Cooperative Highway Research Program, comprising the Highway and River Engineering Division of the Research Council of Alberta, the Department of Highways and Transport of Alberta, the Water Resources Division of the Department of the Environment of Alberta, and the Department of Civil Engineering at The University of Alberta. An extensive study of the elastic properties of a section of full-depth asphalt concrete pavement on a clay subgrade at several locations on a four-lane divided freeway section has been undertaken by the Highways Division of the Research Council of Alberta, with this particular laboratory investigation as a part of the Cooperative Program.

The test project was the new Highway 15-A-1, Alberta, which is located northeast of Edmonton. It starts from the city limits at mile 7.11 and ends just east of the junction of Highway No. 37 at mile 15.19. This highway is a full-depth asphalt concrete pavement constructed on a clay subgrade. The highway subgrade was constructed in the late summer of 1971 and the test sections were completed in the

fall of the same year. The location of the instrumented sections on this highway are at mile 9.44 and mile 11.00 as indicated in FIGURE 3.1.

The asphalt concrete was laid directly on the surface of the compacted subgrade, in three layers with nominal thicknesses of 3, 3 and 2 inches, respectively. The total thickness of the asphalt concrete pavement according to the Contract and Specifications of the Department of Highways and Transport was 8 inches, but due to construction variations it was 7.2 inches at mile 9.44 and 9.3 inches at mile 11.00. The cross-sections of the highway at these two locations are shown in FIGURES 3.2 and 3.3, respectively.

The asphalt used as the asphalt concrete pavement binder was specified as an AC 275 with a minimum viscosity of 275 poises at 140°F and a penetration of 250 at 77°F.

3.2. Instrumentation

During construction of the highway thermocouples and pressure cells were installed within the pavement structure by the staff of the Research Council of Alberta, Highways Division. These installations were at mile 9.44 and mile 11.00, in the inner lane of the westbound lanes on the outer wheelpath.

Standard Copper-Constantan thermocouples were installed at these locations at approximately 2 inch depth increments from the pavement surface within the asphalt concrete pavement, and thereafter at 2 feet intervals within the subgrade to a depth of 96 inches below the pavement surface.

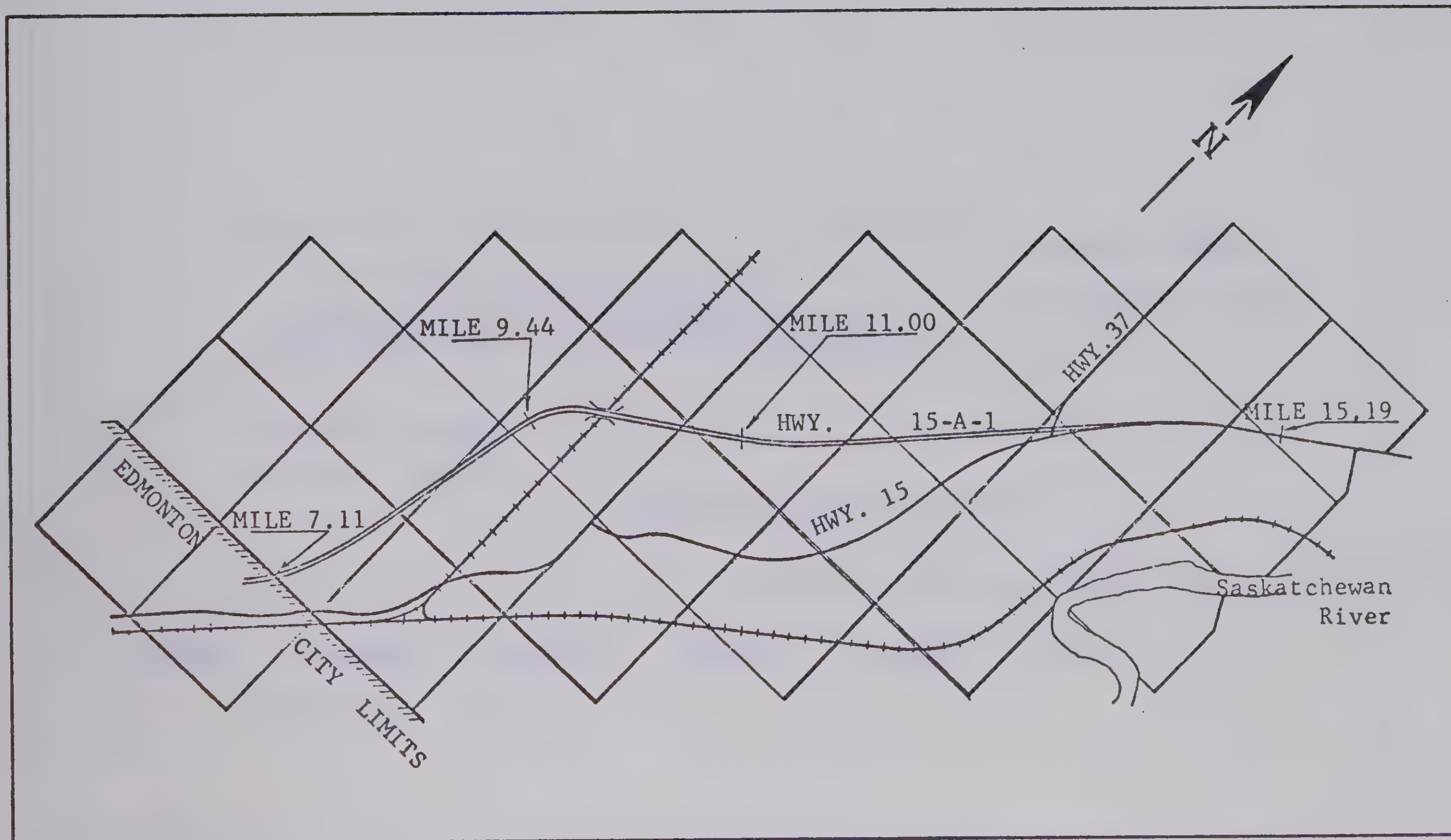


FIGURE 3.1. LOCATION PLAN OF HIGHWAY 15-A-1, EDMONTON TO EAST OF JUNCTION HIGHWAY 37

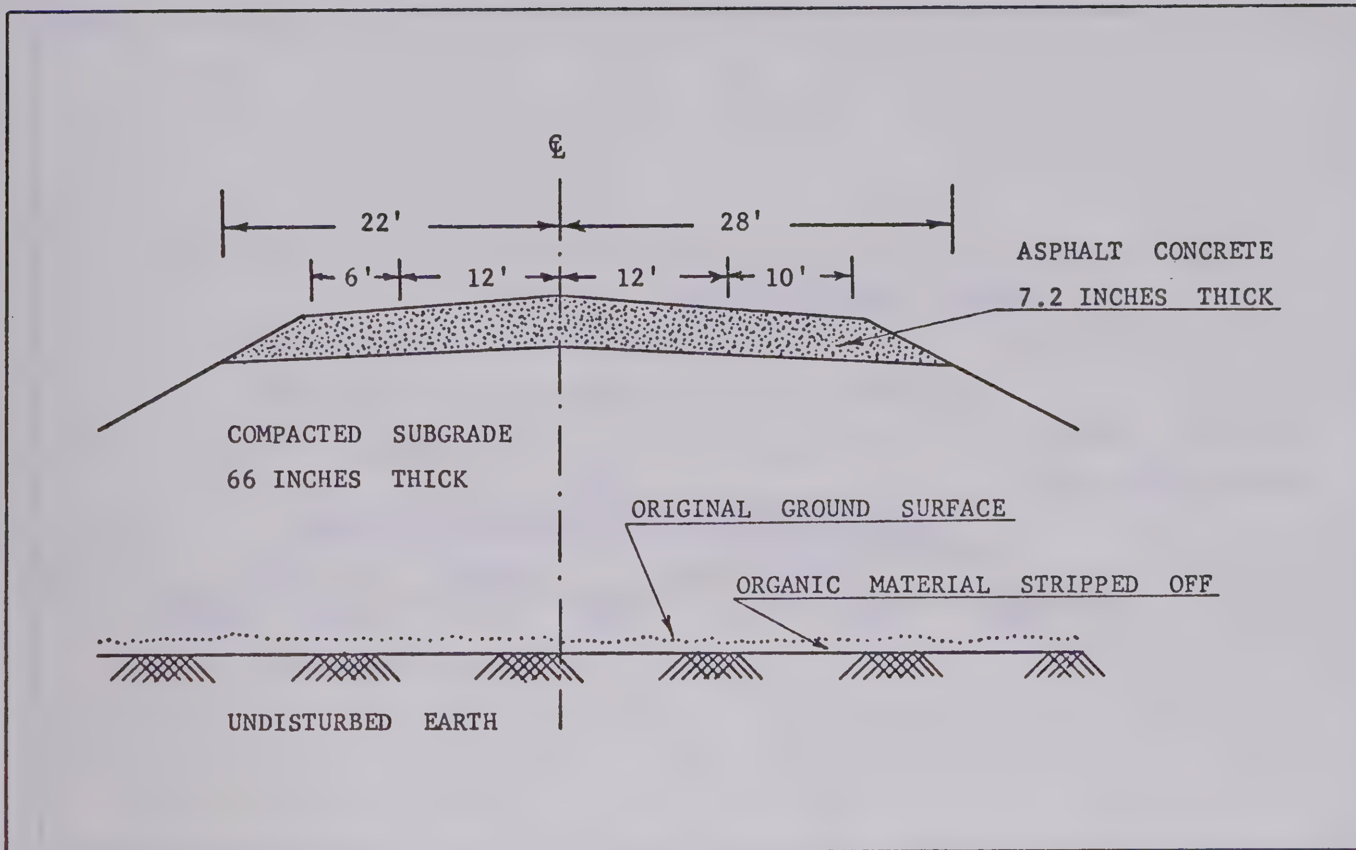


FIGURE 3.2. CROSS-SECTION OF HIGHWAY 15-A-1, AT MILE 9.44

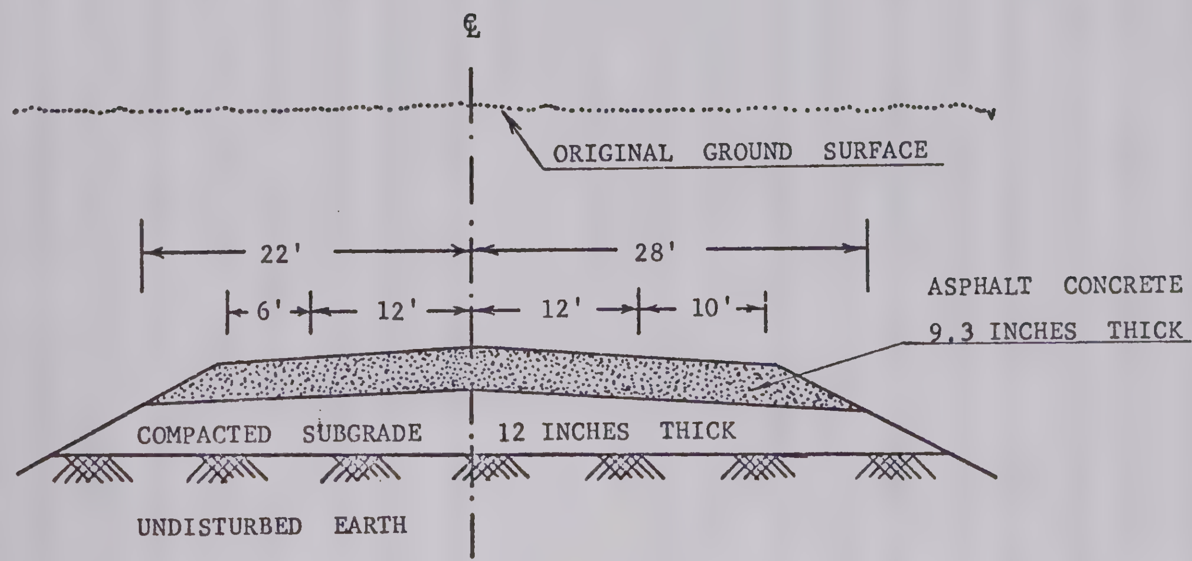


FIGURE 3.3. CROSS-SECTION OF HIGHWAY 15-A-1, AT MILE 11.00

The pressure cells installed in the pavement were fabricated in the laboratory, by the staff of the Research Council of Alberta, Highways Division. This was a half-bridge system with an active gauge in one arm of the bridge and a compensating gauge in the other arm of the bridge. The active gauge was a spiral strain gauge while the compensating gauge was a quarter inch metal foil gauge. These gauges were encased in an aluminum, cylindrical hollow box, 4.5 inches in diameter and 0.5 inches thick, so that the active gauge was placed against the top plate, which also acted as a diaphragm. The pressure cell was connected to a Sanborn 321 recorder. At one particular location, three such pressure cells were embedded in the subgrade such that the tops were flush with the subgrade surface and were 24 inches apart along the outer wheelpath.

3.3. Measurements

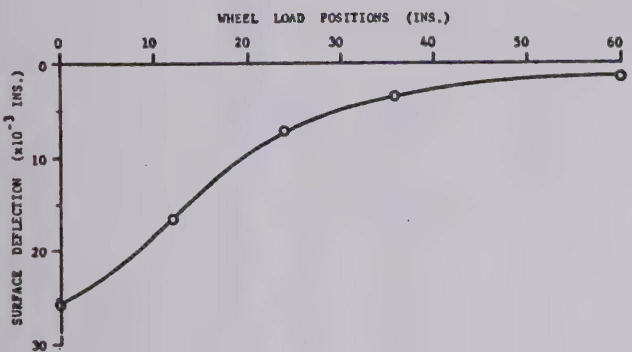
After the second layer of asphalt concrete was laid, static moduli of the pavement and the subgrade were determined from the Benkleman Beam Test according to the procedure described by Shields and Hutchinson (1961). The dynamic moduli of the pavement and the subgrade were determined by the Vibrator Technique according to the procedure described by Shields (1971). Vertical stress on the subgrade under the wheel-load as registered by pressure cells, the temperatures as registered by thermocouples, and surface deflections were measured using the Benkleman Beam Test according to CGRA (1965) rebound procedure. The tests were repeated after the final lift of asphalt concrete was laid. Surface deflections recorded are shown in FIGURE

3.4 a), b), c), and d) as longitudinal surface deflections, while the measured vertical stresses and moduli are tabulated in TABLE III-1.

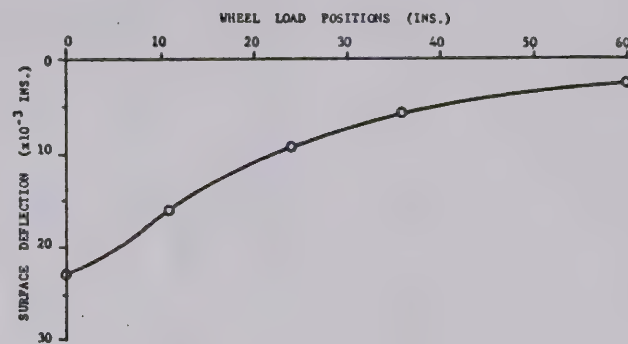
Tests on recovered asphalt concrete were performed to evaluate the properties of the mixture and the asphalt used. Penetration, viscosity, and ring and ball softening point values of the asphalt; and dry density, bulk specific gravity, percent air voids, percent volume of mineral aggregate (VMA), and the percentage of asphalt content in the mixture were determined and are tabulated in TABLE III-2.

These measurements were used subsequently for analyses and comparison with theoretically predicted values.

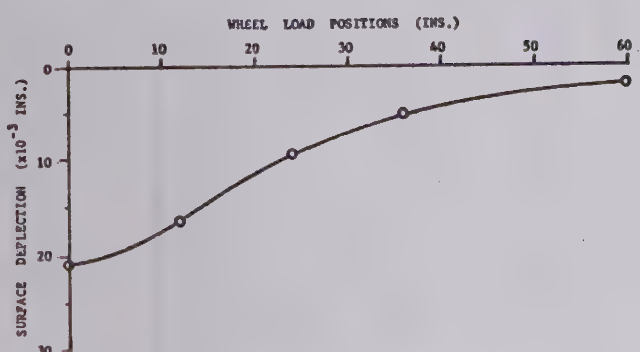
The pressure cells were calibrated by embedding them in sand and recording the output which was then compared with calculated stresses by means of Boussinesq theory. As such the estimated accuracy of the pressure cells are ± 15 percent. This is sufficient to give an idea of the magnitude of stresses induced in the pavement. The accuracy of the thermocouples are ± 1.5°F and that of the dial gauges in the Benkleman Beam are ± 0.001 inches.



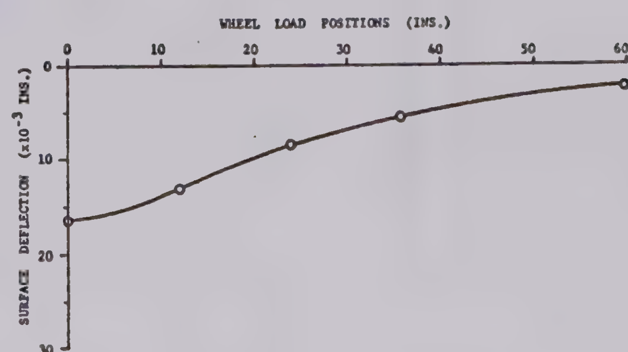
A) MILE 9.44, 5.1 INCHES PAVEMENT



C) MILE 11.00, 5.5 INCHES PAVEMENT



B) MILE 9.44, 7.2 INCHES PAVEMENT



D) MILE 11.00, 9.3 INCHES PAVEMENT

FIGURE 3.4. DEFLECTION PROFILES FROM BENKLEMAN BEAM TESTS ON HIGHWAY 15-A-1

TABLE III-1

FIELD MEASUREMENTS TAKEN FROM HIGHWAY 15-A-1

Location	Pavement Thickness	Static Test					Dynamic Test			
		Vertical Stress	Pavement Temperature		Modulus (psi)		Pavement Temperature		Modulus (psi)	
			Bottom	Top	$E_{pavement}$	$E_{subgrade}$	Bottom	Top	$E_{pavement}$	$E_{subgrade}$
mile	ins	psi	°F	°F	psi	psi	°F	°F	psi	psi
9.44	5.1	27.2	60.0	75.0	269300	14600	57.0	61.0	1410000	31000
WBL,OWP,IL	7.2	11.8	42.0	42.0	454000	13600	42.0	42.0	1700000	34400
11.00	5.5	18.4	42.0	44.0	300000	14000	43.0	46.0	1830000	32700
WBL,OWP,IL	9.3	11.9	36.0	39.0	464400	14200	36.0	39.0	1930000	40200

TABLE III-2

RECOVERED PROPERTIES OF ASPHALT CONCRETE FROM HIGHWAY 15-A-1

Location	Dry Density	Bulk Specific Gravity	Asphalt Content	Air Voids	VMA	Penetration at		Viscosity at 60°C	Ring & Ball Softening Point	C_v	C'_v
						25°C	4°C				
mile	pcf		%	%	%			poise	°C		
9.44	142.3	2.62	5.3	6.5	17.2	186	46	398	39.4	0.85	0.83
11.00	143.5	2.62	5.3	5.7	16.5	169	45	572	40.0	0.86	0.84

NOTE : VMA : Voids in Mineral Aggregate

C_v : Volume Concentration of Aggregate

C'_v : Corrected Volume Concentration of Aggregate

CHAPTER IV

TEST EQUIPMENT, PROCEDURE AND PROGRAM

4.1. General

This chapter summarizes the testing program and the testing procedures followed in this investigation. A description of the repeated loading triaxial test apparatus and associated equipment is given. Methods of sample preparation and compaction of samples are briefly described.

4.2. Repeated Loading Triaxial Test Apparatus

The primary objective of the testing program was the determination of the resilient modulus of the fine-grained cohesive subgrade material under various deviator stresses. A repeated loading triaxial test apparatus was needed for this purpose and the equipment designed and constructed after the model of Seed and Fead (1959) was put into operation as part of this investigation.

A steel framework made of channel sections was built for seating three triaxial cells along with their loading devices and allied equipment required for their operation. All the three loading devices were designed to produce the same load characteristics, so that consistent results could be anticipated.

Load is applied to a specimen in a triaxial cell by means of a piston and loading yoke, the load being repeatedly applied to the yoke by means of an air-pressure cylinder mounted below the triaxial cell. For this purpose compressed air is passed through a regulator and stored at a constant pressure in a reservoir tank. The tank is connected through a solenoid valve to the pressure cylinder. When the valve is open, air pressure is transmitted through the cylinder and loading yoke to the specimen. When the valve is closed, the air in the pressure cylinder passes through an exhaust pipe in the valve and the load is removed.

The load applied to the specimen is varied by regulating the air pressure in the cylinder. By calibrating the load against the air pressure as recorded by a pressure gauge, the desired load can readily be obtained.

Application of pressure to the air-pressure cylinder is controlled by a solenoid-operated three-way valve. Movement of the valve to admit air or exhaust air from the pressure cylinder is controlled by an electrical timing unit.

The specimen in the triaxial cell is surrounded with water. Air pressure from the reservoir tank is applied through a pressure supply valve in the base of the triaxial cell, which constituted the confining pressure and is transmitted to the specimen through the confining water. The confining pressure is recorded by a pressure transducer, which is connected to a strain indicator. Knowing the calibration factor of the pressure transducer, the strain indicator reading is converted to obtain pressure.

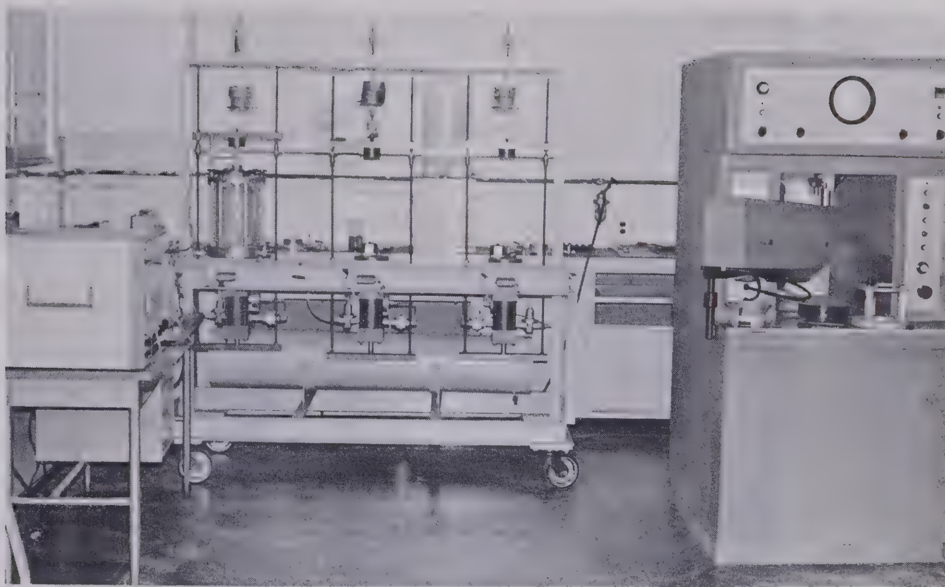
The specimen is loaded axially by placing the entire cell under the loading yoke. Deformation of the specimen is measured by a LVDT, which is clamped to the piston of the triaxial cell applying the load and the moving end is screwed to the cell cap. The magnitude of the load is measured by a load cell on the loading yoke which sits with a firm contact on the piston of the triaxial cell.

The LVDT and the load cell are connected to an ultra-violet recorder through a galvanometer and signal conditioner unit. The loads and deformations are recorded on a light-sensitive paper in the ultra-violet recorder. The calibration of the LVDT and the load cell is so matched with the galvanometer and signal conditioner unit, that the magnitude of deformation and load is read directly from the recording paper.

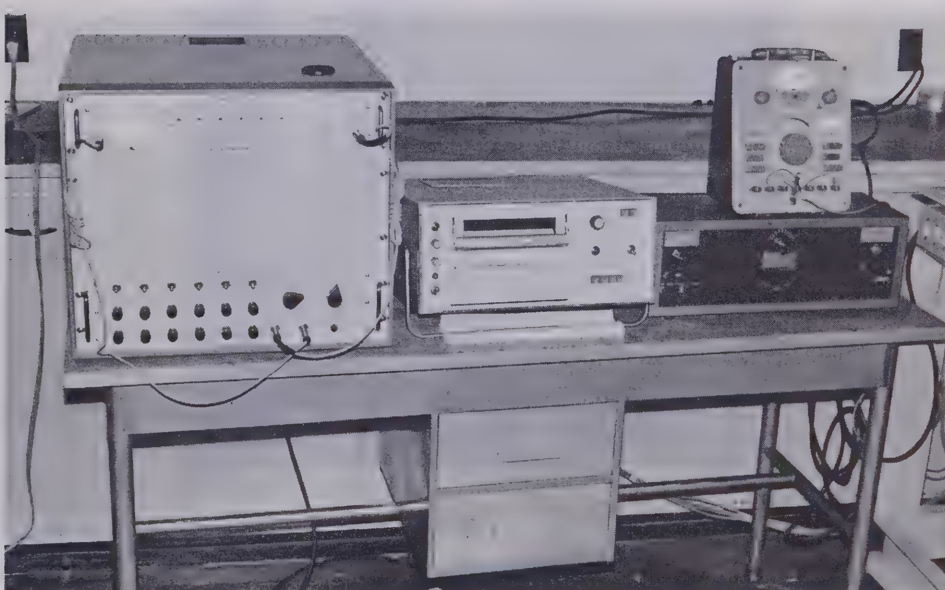
The number of load applications to a specimen is recorded automatically in a six-digit resettable counter connected to the control valve.

The triaxial cell used is a standard size suitable for testing cylindrical samples 4 inches in diameter by 8 inches high, as described by Bishop and Henkel (1962), except that the recess under the base was adjusted so that the cell could sit on the seat in the frame. A threaded hole on the cap of the triaxial cell was made for the LVDT to be screwed to the cap.

PLATES 1 and 2 show the test apparatus with further details given in APPENDIX A.



A) GENERAL VIEW



B) RECORDING EQUIPMENT AND TIMING UNIT

PLATE 1. REPEATED LOADING TRIAXIAL APPARATUS AND EQUIPMENT USED IN TESTING PROGRAM

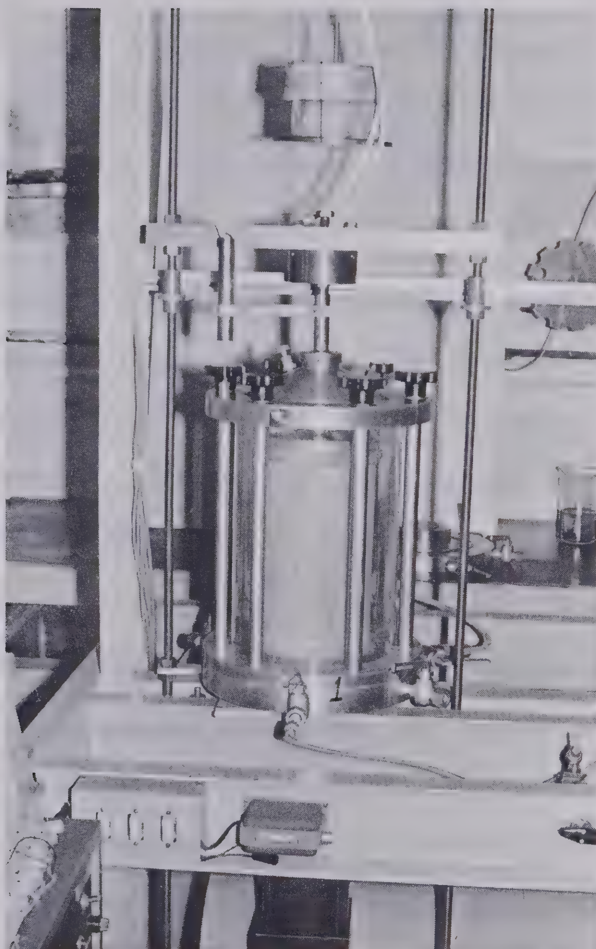


PLATE 2. CLOSE-UP OF AN ASSEMBLED TRIAXIAL CELL

4.3. Preparation of Soil Samples

The size and shape of the samples to be prepared, as determined from the test apparatus, were essentially 4 inches in diameter and 8 inches high cylindrical specimens. Specifications of the Department of Highways and Transport of Alberta required the pavement subgrade to be compacted to one hundred percent Standard Proctor Density at optimum moisture content. Hence it was decided to maintain the same requirement for compaction of laboratory samples.

The embankment material of the prototype pavement was obtained from borrow pits in the field. This material was spread on a flat surface and allowed to air-dry. After air-drying it was crushed and passed through a No. 4 sieve. Material passing through this sieve was used for sample preparation.

The Standard ASTM D698-70 Test for determining moisture-density relation of soils, was performed with the soil and the optimum moisture content and the corresponding dry density was determined. Hygroscopic water content of the soil was determined and distilled water was added accordingly to obtain the desired moisture content. One half percent extra water was added to allow for evaporation during mixing. Soil was mixed thoroughly by hand for five minutes. Hand mixing of the soil was done, because of the large amount (4,000 grams) of soil required for the preparation of one sample, which could not be accommodated in the mechanical mixer available in the laboratory at The University of Alberta. Material for six samples was mixed at the same moisture

content and placed in a plastic bag. The mouth of the bag was tied tightly and the bag was stored in the moisture room for twenty-four hours to allow for moisture migration within the soil.

4.4. Compaction of Samples

4.4.1. Impact Compaction

At the beginning of the investigation, the kneading compactor was not available. As a result, samples were hand compacted using a drop-hammer hand compactor. The compactor was a 5.5 pound drop-hammer with a 12 inch free fall, as specified for Standard ASTM D698-70 Test. The mould used was a 4 inch diameter and 8 inch high split mould with a 2 inch collar at the top. Trial compactions were performed to determine which procedure could be used to attain the Standard ASTM D698-70 Densities. It was found that soil compacted in five layers with twenty-five blows per layer was close to the required density. To control the uniformity of samples, material required for preparation of one sample was divided into five equal parts. Each part was placed in the mould and spread evenly by hand after which twenty-five blows of the drop-hammer were applied around the mould. After the last blow to the fifth layer, the collar was removed and the excess material was trimmed.

4.4.2. Kneading Compaction

The kneading compactor was installed in the laboratory at The University of Alberta and was made available for use at a very late stage of the investigation, hence only a limited amount of work could

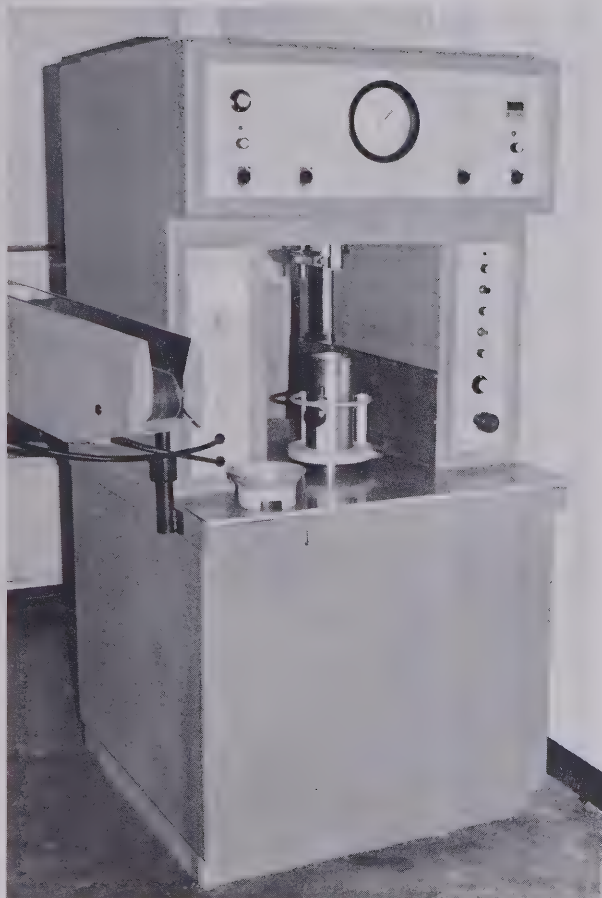
be done with samples prepared by kneading compaction. The kneading compactor was calibrated by trial and error so as to attain Standard ASTM D698-70 Densities for the particular sample size.

From the experience gained it was observed that Standard ASTM D698-70 Densities were attained by compacting the sample in five layers, with twenty-five tamps per layer and a ram dwell time of 1.5 seconds. For soils at optimum moisture content, this density was achieved by applying a foot pressure of 150 psi. However, when the soil was wet of optimum moisture content, this foot pressure was too high and caused excessive penetration of the foot (about one and one half inches). Consequently, the foot pressure was reduced to 100 psi, which gave a foot penetration of about one quarter inch. The details of calibration are included in APPENDIX B.

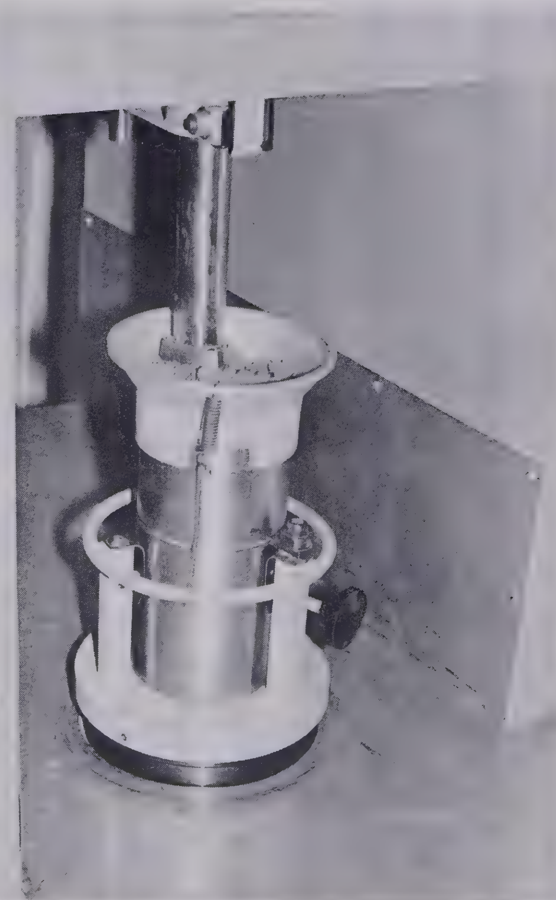
PLATE 3 shows the kneading compactor with further details given in APPENDIX B.

4.5. Outline of Testing Program

The testing program consisted of repeated loading triaxial tests on compacted clay samples to determine the resilient modulus (M_R) under various deviator stresses. It was decided to use clay samples at optimum moisture content and wet of optimum moisture content to see how the resilient modulus would be affected under adverse conditions of construction. It was also decided to see how different methods of compaction affected the resilient modulus. For this purpose, three series of tests were run. One series of samples were prepared with impact compaction, one series with kneading compaction, and one series



A) GENERAL VIEW



B) COMPACTION IN PROGRESS

PLATE 3. ELECTRONIC - HYDRAULIC KNEADING COMPACTOR

with field cores obtained with Shelby Tubes. The results of the tests were presented as points on curves of M_R versus deviator stress. In some cases a single specimen was tested more than once, an acceptable procedure according to Terrel (1972), provided that the stress levels and the number of repetitions were not excessive.

All the samples were subjected to repeated loading at the rate of 20 load applications per minute, with a load duration of 0.25 seconds. The testing program followed in this investigation is summarized in TABLE IV-1. The program is divided into three main series: a) tests on impact compaction samples (L series), b) tests on subgrade cores (F series), and c) tests on kneading compaction samples (K series).

Available literature indicated that a confining pressure of 3 psi was usually used in determining the resilient modulus of subgrade soil in the laboratory. This magnitude of lateral pressure is usually exhibited in the subgrade near the pavement-subgrade interface, and is dependent on the thickness of the pavement. Thus a confining pressure of 3 psi was adopted for use in this testing program.

TABLE IV-1

SUMMARY OF TESTING PROGRAM

Test Series	Sample Number	Test Conditions: No. of times the sample was used	Test Conditions: Desired Deviator Stresses (psi)	Test Conditions: Confining Pressure (psi)	Remarks
L	1 2 3	2 1 2	8.0, 16.0 14.0 10.0, 25.0	3.0 3.0 3.0	Samples compacted by impact method (hand compaction) at around optimum moisture content.
L	4 5 6	3 2 3	4.0, 7.0, 14.0 6.0, 8.0 5.0, 9.0, 12.0	3.0 3.0 3.0	
L	7 8 9 10 11 12	1 1 1 1 2 2	4.0 7.0 9.0 14.0 18.0, 24.0 22.0, 29.0	3.0 3.0 3.0 3.0 3.0 3.0	
L	13 14 15 16 17	1 1 1 1 1	4.0 8.0 11.0 15.0 20.0	3.0 3.0 3.0 3.0 3.0	Samples compacted by impact metnod (hand compaction) at wet of optimum moisture content.
F	5 6 7	4 3 4	4.0, 6.0, 8.0, 18.0 16.0, 20.0, 24.0 10.0, 12.0, 14.0, 23.0	3.0 3.0 3.0	Subgrade cores obtained from the prototype pavement.
K	1 2 3	4 2 4	2.0, 6.0, 12.0, 16.0 4.0, 10.0 2.0, 6.0, 8.0, 14.0	3.0 3.0 3.0	Samples compacted by automatic kneading compactor at around optimum moisture content.
K	4	3	2.0, 6.0, 11.0	3.0	Samples compacted by automatic kneading compactor at wet of optimum moisture content.
K	5 6	2 4	8.0, 11.0 2.0, 5.0, 6.0, 12.0	3.0 3.0	

CHAPTER V

RESULTS AND DISCUSSION

5.1. General

This chapter is divided into three major sections. In the first section, curves are presented from which the stiffness modulus of asphalt concrete can be determined theoretically. The second section consists of the subgrade materials characterization, a part of which is derived from the results of the laboratory repeated loading triaxial tests on the subgrade soil. The third section uses the moduli values provided by the first two sections and involves structural analyses to find an effective pavement model for predicting surface deflections and stresses induced on the subgrade, with the help of the Chevron 5-layered elastic theory computer program.

5.2. Asphalt Concrete Stiffness

The top layer of a flexible pavement usually consists of asphalt concrete whose stiffness varies with temperature and loading time as noted by Van der Poel (1954). Such being the case for the problem under consideration, it was imperative to determine the stiffness of the asphalt mixture under conditions of varying temperatures and loading times.

The stiffness of the asphalt mixture used in the pavement was determined by an indirect method based on the recovered properties of the asphalt concrete (TABLE III-2) and nomographs presented by Heukelom and Klomp (1964), using the procedure suggested by McLeod (1969). The indirect method and its development is discussed in CHAPTER II. A master curve to obtain stiffness of the asphalt concrete at various loading times for a reference temperature of 60°F was determined and is presented in FIGURE 5.1. In order to use this master curve over a range of temperatures, the shift factor concept, as described by Finn (1967) was used and a variation of shift factor with temperature is shown in FIGURE 5.2. Sample calculations for the preparation of FIGURES 5.1 and 5.2, along with a typical example of using these figures are included in APPENDIX D.

Finn (1967) has shown that for a material exhibiting thermorheologically simple behaviour, the position of the modulus curve but not its shape, is altered on the time scale by temperature changes. That is, if one were to define the modulus for a wide range of times at a series of temperatures, these curves at different temperatures are shifted only along the time axis. If a reference temperature T_o is chosen then the amount by which another temperature curve is shifted along the time axis so as to superimpose on the reference temperature curve, is known as the shift factor and is physically defined as:

$$A_T = \frac{t_T}{t_o} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 5.1$$

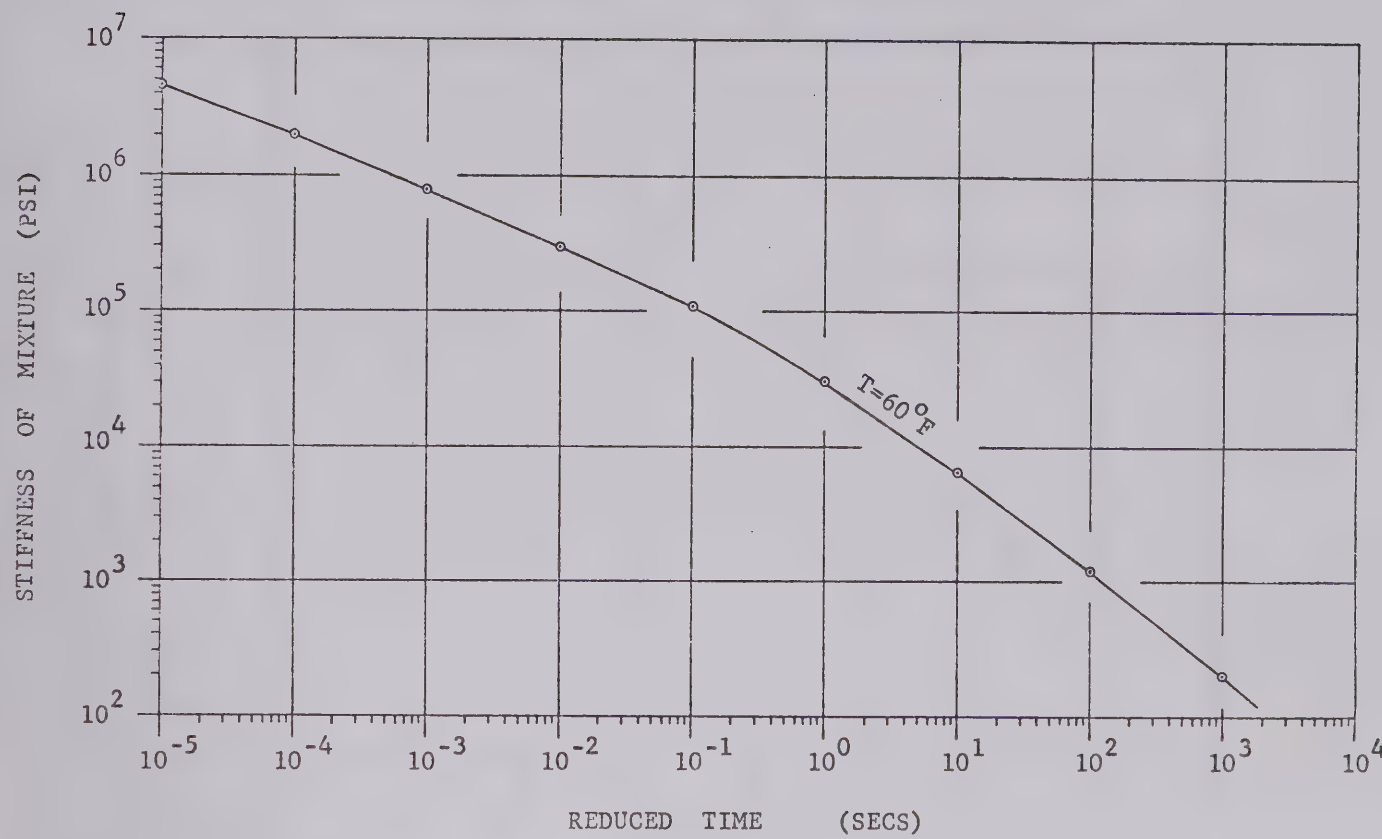


FIGURE 5.1. EFFECT OF LOADING TIME ON STIFFNESS OF ASPHALT CONCRETE MIXTURE

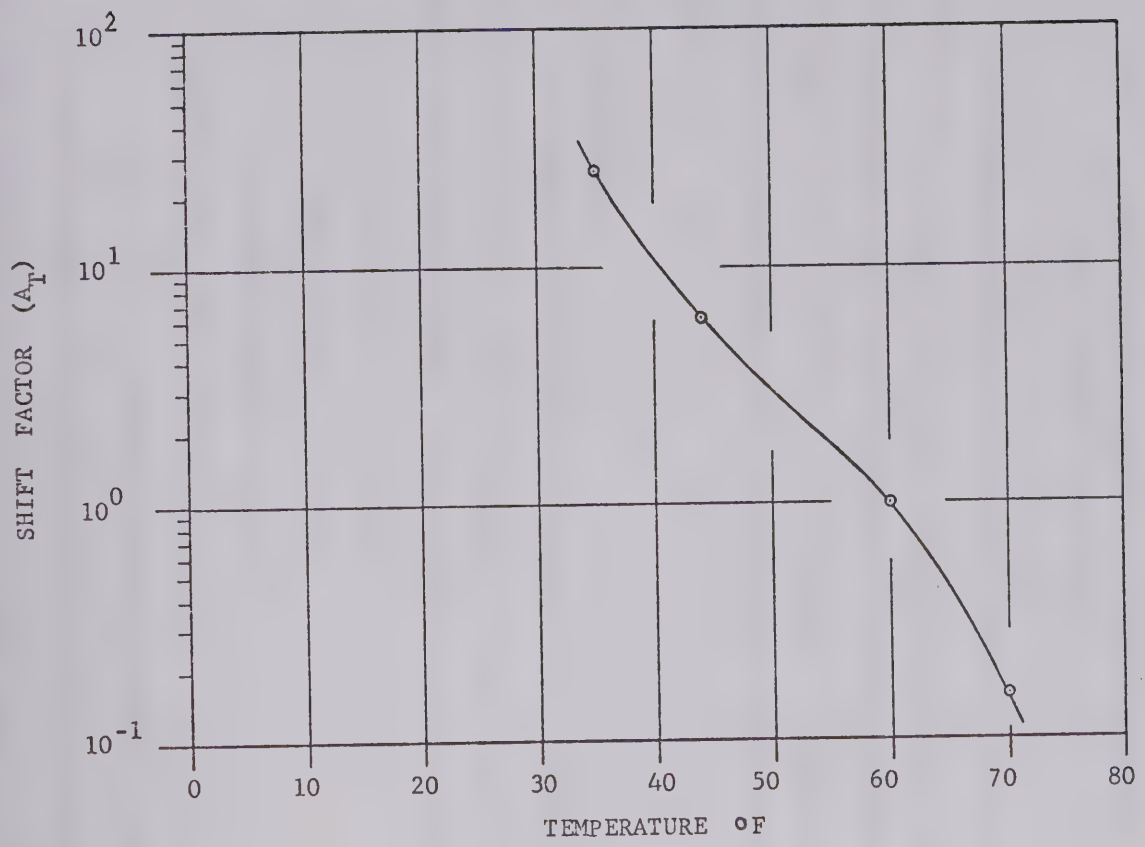


FIGURE 5.2. VARIATION OF SHIFT FACTOR WITH TEMPERATURE

where,

A_T = shift factor;

t_T = time required to observe a phenomenon at temperature T; and

t_o = time required to observe the same phenomenon at some reference temperature T_o.

This procedure helps to reduce the family of curves at different temperatures to a single curve for a particular reference temperature. In addition, the plot of shift factor versus temperature enables the determination of shift factor for any intermediate temperature within the range of plotted temperature, thereby reducing many additional computations.

5.3. Subgrade Soil

The subgrade soil under the pavement was an inorganic clay with medium plasticity and can be classified as CL type of soil in the Unified Classification System. The characteristics of the soil are:

Liquid Limit = 38.5%

Plastic Limit = 16.4%

Shrinkage Limit = 14.3%

ASTM D698-70 TEST: Maximum Dry Density = 112.2 lbs/ft^3

Optimum Moisture Content = 15.2%.

Samples prepared in the laboratory were tested immediately after their preparation. The first set of three samples of the L test series were subjected to a minimum of 25,000 load repetitions, detailed calculations of which are included in APPENDIX C. It was observed from

the results of this series that the resilient modulus did not change significantly after 5,000 load applications. Thus it would be reasonable to assume that the resilient modulus at 5,000 load repetitions is representative of the material under the particular test conditions. Although other investigators have chosen to compare results at 25,000 load repetitions, this shorter test procedure appears justified, in view of the preliminary testing.

The results obtained from the laboratory testing program of the subgrade soil are summarized in TABLE V-1. This table gives the resilient moduli at 5,000 load repetitions, of samples subjected to various deviator stresses, along with their water contents and dry densities. The estimated errors in the resilient modulus determination varied from 0.9 to 14.3 percent, the magnitude of error at a low deviator stress being high. However, the majority of errors were in the range of one to four percent. A sample calculation of the error is given in APPENDIX A. On a close examination of the table it will be seen that as the deviator stress increases the resilient modulus decreases and so also does the error.

The subgrade soil tested in the laboratory under repeated loading was divided into three test series designated as L, F, and K test series. Series L comprises samples compacted by impact compaction, the F test series were Shelby Tube cores obtained from the field, and the K test series were samples compacted by kneading compactor. The results of the three test series given in TABLE V-1 are plotted separately to show the variation of resilient modulus with stress intensity.

TABLE V-1

SUMMARY OF LABORATORY REPEATED-LOAD TEST RESULTS

Test Series	Sample Number	Water Content %	Dry Density pcf	Deviator Stress psi	Confining Pressure psi	Resilient Modulus at 5000 Load Repetitions psi	Estimated Error in M_R ± %
L	1	16.4	105.5	8.0	3.0	8550	2.8
				16.0	3.0	4650	1.4
	2	16.9	106.9	14.0	3.0	5600	1.5
	3	17.4	107.7	10.0	3.0	4000	2.1
				25.0	3.0	3100	1.0
L	4*	15.2	110.9	4.0	3.0	16000	7.1
				7.0	3.0	8000	3.2
				14.0	3.0	7000	1.6
	5*	15.0	108.9	6.0	3.0	8350	3.8
				8.0	3.0	2100	2.6
	6*	15.1	111.8	5.5	3.0	9800	4.3
				9.0	3.0	4250	2.3
				12.0	3.0	3700	1.8
L	7	14.8	109.3	4.0	3.0	21350	8.3
	8	15.2	109.2	7.0	3.0	11200	3.5
	9	14.6	110.1	9.0	3.0	7650	2.5
	10	15.3	111.4	14.0	3.0	9350	1.7
	11	15.1	111.3	18.0	3.0	6200	1.2
				24.0	3.0	5050	1.0
	12	14.1	112.2	22.0	3.0	4950	1.1
				29.0	3.0	4050	0.9
L	13	19.3	107.9	4.0	3.0	3300	5.1
	14	19.3	108.6	8.0	3.0	1250	2.6
	15	18.3	110.2	11.0	3.0	2550	1.9
	16	19.2	108.4	15.0	3.0	1150	1.4
	17	19.0	108.8	20.0	3.0	2400	1.1
F	5	20.1	109.0	4.0	3.0	6100	5.1
				6.0	3.0	5950	3.7
				8.0	3.0	10100	3.2
				18.0	3.0	8900	1.4
	6	18.0	110.6	16.0	3.0	9700	1.6
				20.0	3.0	8650	1.2
				24.0	3.0	8250	1.0
	7	22.2	105.7	10.0	3.0	4600	2.1
				12.0	3.0	5500	1.8
				14.0	3.0	7150	1.6
				23.0	3.0	4950	1.0
K	1	15.1	112.5	6.0	3.0	21800	5.6
				12.0	3.0	10300	2.0
				16.0	3.0	9300	1.4
				2.5	3.0	21350	14.3
	2	15.2	112.2	4.0	3.0	15250	6.9
				10.0	3.0	12100	2.5
	3	15.1	112.3	2.0	3.0	13350	13.0
				8.0	3.0	12550	3.1
				14.0	3.0	9750	1.7
				6.0	3.0	14550	4.5
K	4	18.2	108.4	2.0	3.0	8500	11.2
				6.0	3.0	5000	3.5
				11.0	3.0	2400	1.9
K	5	18.0	110.2	8.0	3.0	1450	2.6
				11.0	3.0	1350	1.9
	6	18.3	110.1	2.0	3.0	3200	10.2
				5.0	3.0	2350	4.1
				6.0	3.0	2500	3.4
				12.0	3.0	1850	1.8

Note : Series L - Impact Compaction
Series F - Shelby Tube Cores
Series K - Kneading Compaction

Standard ASTM Density - 112.2 lbs/ft^3
OMC - 15.2 %

* Suspected malfunction of the apparatus; repeated test with L 7,8,9,10,11,12.

5.3.1. Laboratory Prepared Samples

FIGURE 5.3 shows the variation of resilient modulus with deviator stress for the L test series. The results were comparable to those observed by Monismith et al. (1967) and Seed et al. (1967) for a similar material. It is seen that for samples near the optimum moisture content, the rate of decrease in the resilient modulus was very pronounced with a slight increase in the deviator stress especially in the low range of deviator stresses (up to 8 psi), while in the higher range of deviator stresses, the rate of decrease in the resilient modulus with increase in the deviator stress was low. It is also observed that for samples wet of optimum moisture content, the pronounced decrease in the resilient modulus in the low deviator stress range is not present and the rate of decrease in the resilient modulus with increase in the deviator stress over the whole range of deviator stresses is moderate. In addition to this, the curve as a whole shifts to a lower order of resilient modulus, indicating that increasing the moisture content above the optimum results in a high resilient deformation which is undesirable in a pavement structure.

The samples of the L test series were prepared by hand compaction and preparation of identical samples having similar densities was difficult. Hence, the results obtained from testing these samples would be expected to show some variation. It is seen that for this type of compaction, a variation of one percent in moisture content and three pounds per cubic foot in dry density within a set of samples, does not affect the resilient modulus significantly.

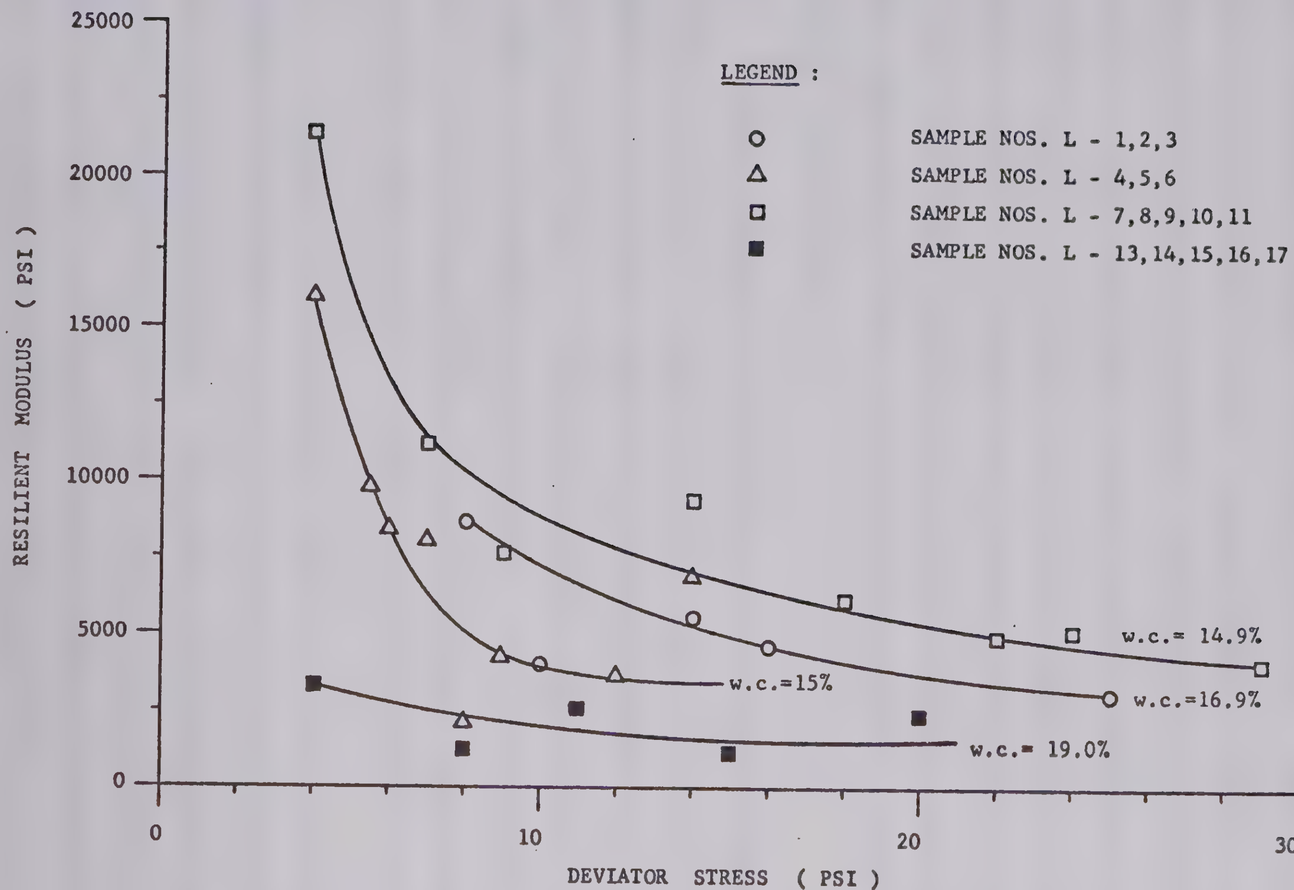


FIGURE 5.3. EFFECT OF STRESS INTENSITY ON RESILIENT MODULUS FOR L TEST SERIES

The effect of stress intensity on resilient modulus for K test series is shown in FIGURE 5.4. The trend of the curves are similar to those presented in FIGURE 5.3 and discussed earlier. The samples were mechanically compacted resulting in more uniform and closer to identical samples being obtained (TABLE V-1). Except for points (1) and (2), the results fit in a smooth curve with low scatter. Another test was run with the same test conditions as was used for samples which yielded points (1) and (2). The new results obtained were plotted in FIGURE 5.4 and it was found that points (1) and (2) shifted to points (1A) and (2A), respectively, to fall on the curve indicating that there was some error in the first test.

A foot pressure of 75 psi was used while preparing sample K4. The foot penetration was about one quarter inch and the dry density achieved was lower than that of the Standard ASTM D698-70 Test for the same moisture content. Consequently, the foot pressure was increased to 100 psi for preparing samples K5 and K6. The foot penetration in this case was about one half inch and the dry density was increased to that of the Standard Density at that particular moisture content.

It would be expected that at identical moisture contents, samples with lower densities would yield lower resilient moduli than samples with higher densities. But FIGURE 5.4 indicates that sample K4, with a lower density than those of K5 and K6, gave higher resilient moduli than those for K5 and K6 in the same range of deviator stresses. It is rather interesting to note that the amount of foot penetration during compaction of samples effects the resilience characteristics of

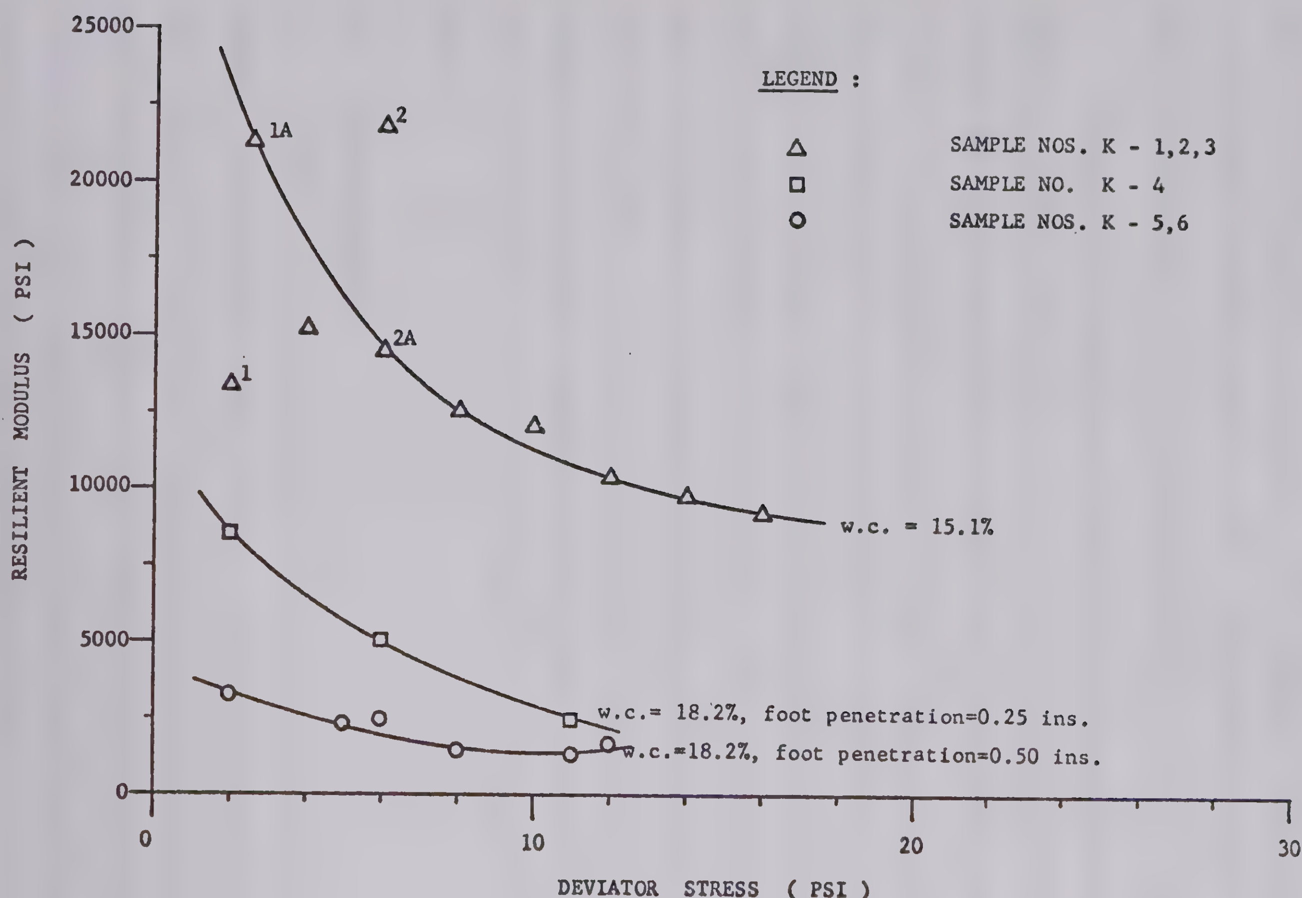


FIGURE 5.4. EFFECT OF STRESS INTENSITY ON RESILIENT MODULUS FOR K TEST SERIES

clayey soils and the results here show that samples prepared with a lower foot penetration gave a higher resilient modulus than those prepared with a higher foot penetration. The effect of foot penetration on the resilience characteristics of soils, also noted by others warrants further investigation but is considered beyond the scope of this thesis.

There was no significant effect on the resilient modulus when samples were tested more than once. It can be seen from FIGURES 5.3 and 5.4 that the test results fit reasonably well in the curvilinear relationship with no appreciable scatter. Since a single sample was used up to four times in these tests, the results show that there is little effect on the resilient modulus by repeated use of the same sample, which was also observed by Terrel (1972). However, this aspect was not verified by a detailed investigation, but from the results of this investigation there is reason to believe that a sample may be used several times to produce compatible results, provided that the applied stress, the resulting strain and the number of load repetitions are kept low.

5.3.2. Field Samples

FIGURE 5.5 shows the variation of resilient modulus with deviator stress for the F test series. Only one set (comprised of three samples) was used in the testing program and the results of these tests show a scatter of points and no definite curve can be drawn through these points. However, most of these points could well be included in a band, with a curve being drawn through the upper and lower series of points. If this band is treated as representative of the

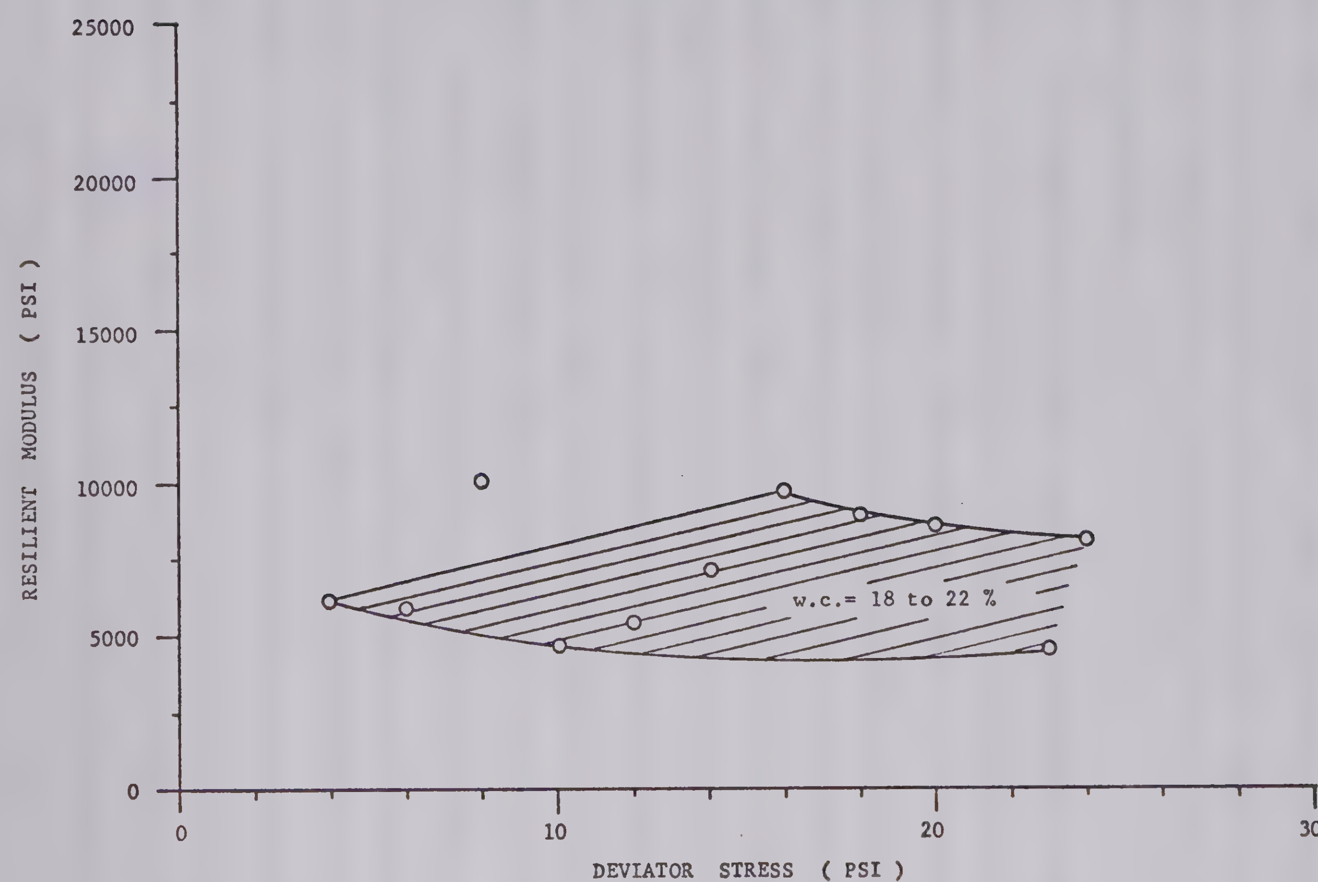


FIGURE 5.5. EFFECT OF STRESS INTENSITY ON RESILIENT MODULUS FOR F TEST SERIES

variation of the resilient modulus with the deviator stress for this test series, it can be seen that the trend of this band is similar in nature to that of the curves in FIGURE 5.4, with the upper and lower boundaries resembling the 15.1 percent and 18.2 percent water content curves, respectively.

The samples of the F test series as stated earlier in this chapter, were Shelby Tube cores and these were subjected to some disturbance while sampling. The recovered length of the samples were less than 8 inches (between 6 and 8 inches), making it difficult to maintain the length to diameter ratio of two, as in the case of laboratory prepared samples. These could possibly be one of the reasons responsible for the wide scatter of test results in this series, but it is considered that the primary reason for the scatter resides in the fact that of the three samples tested, no two samples possessed identical moisture contents and dry densities, as revealed in TABLE V-1.

From the experience thus gained by testing the field samples, it is evident that great care must be exercised while obtaining field samples. In future, if block samples are obtained rather than cores, the size of the block being large enough so that at least three samples could be carved from it, the samples would be subjected to a minimal disturbance while sampling. Therefore, it could be expected that test samples carved from the block would possess identical properties and the test results would be more consistent.

5.4. Structural Analysis

A difficult part in predicting stresses and deflections in a pavement system using the multi-layered elastic theory computer programs, is the selection and assignment of proper material properties of the various layers from subgrade to surface of the pavement. Terrel and Krukar (1970) found it difficult to assign appropriate moduli values to the pavement materials at various times during the pavement's life and have suggested to use the pavement properties at the time of field measurements, which would then make this type of analysis effective and establish the validity of the elastic layer theory.

The pavement under study was a full-depth asphalt concrete pavement and the materials contained therein are the asphalt concrete and the subgrade soil, whose proper moduli values are essential for the effective use of the elastic theory. The modulus of the asphalt concrete was obtained from the curves presented in FIGURES 5.1 and 5.2. Laboratory resilient modulus test results (FIGURES 5.3, 5.4, and 5.5) on the embankment material were accepted as representative moduli values for the subgrade soil. Pavement models were formulated which contained a maximum of five layers in order to be used with the Chevron 5-layered elastic theory computer program. Various combinations in the number of subgrade and asphalt concrete layers were used to arrive at a pavement model which would yield reasonable predictions of pavement responses.

Since the predicted pavement responses were compared with the pavement responses obtained from the CGRA Benkleman Beam Test, a wheel-load of 9,000 pounds with a tire pressure of 80 psi was used in the

structural analysis. Although the actual loading was with a vehicle having an 18,000 pound axle loading with dual tire configuration, the simplifying assumption of single rather than dual contact areas has been made. From available literature an appropriate value of Poisson's ratio for asphalt concrete was assumed to be 0.33 and that for the subgrade soil between 0.4 and 0.5. The modulus values were assigned to the various layers and the Chevron 5-layered elastic theory computer program was used to compute the stresses and deflections.

5.4.1. Single-Layer Pavement

The pavement system was analysed to see the effect on stresses and deflections by dividing the subgrade into layers. The results are presented in TABLE V-2 and the deflection profile for each case is shown in FIGURE 5.6. During field measurements at mile 9.44 it was observed that the temperature of asphalt concrete in the pavement was uniform from top to bottom at 42°F. In the analysis, the asphalt concrete was maintained as a single layer and the stiffness assigned to it from FIGURES 5.1 and 5.2 was that which corresponded to a temperature of 42°F and a loading time of 0.1 seconds. The subgrade was treated as a single layer with semi-infinite thickness and the effect of assigning low and high moduli values were investigated.

In one case, a modulus value of 10,000 psi was assigned to the subgrade. This modulus value corresponds to a deviator stress of approximately 12 psi (FIGURE 5.4), which is likely to be expected in the subgrade at the pavement-subgrade interface for this pavement thickness. The computed center point stresses and deflections are

TABLE V-2

COMPUTED STRESSES AND DEFLECTIONS FOR A SINGLE-LAYER PAVEMENT

MILE 9.44, PAVEMENT TEMPERATURE 42°F, PAVEMENT THICKNESS 7.2 INS., LOADING TIME 0.1 SECONDS

Layer Thickness ins.	Poisson's Ratio	Average Layer Temperature °F	Moduli and Stiffness of Pavement (psi) A	B	C	D	E
7.2	0.33	42.0	270000	270000	270000	270000	270000
20.0	0.40	-	-	-	-	-	10000
20.0	0.40	-	-	-	-	-	15000
26.0	0.40	-	-	-	-	-	20000
30.0	0.40	-	-	-	-	10000	-
36.0	0.40	-	-	-	-	15000	-
66.0	0.40	-	-	-	10000	-	-
Semi Infinite	0.50	-	10000	25000	25000	25000	25000
SURFACE DEFLECTION UNDER THE WHEEL ($\times 10^{-3}$ ins.)			23.5	12.8	21.4	20.4	19.4
VERTICAL STRESS ON SUBGRADE UNDER THE WHEEL (psi)			11.5	18.8	11.3	11.4	11.6

Measured parameters under the wheel : a) Surface Deflection : 20.9×10^{-3} ins.
b) Vertical Stress on Subgrade : 11.8 psi.

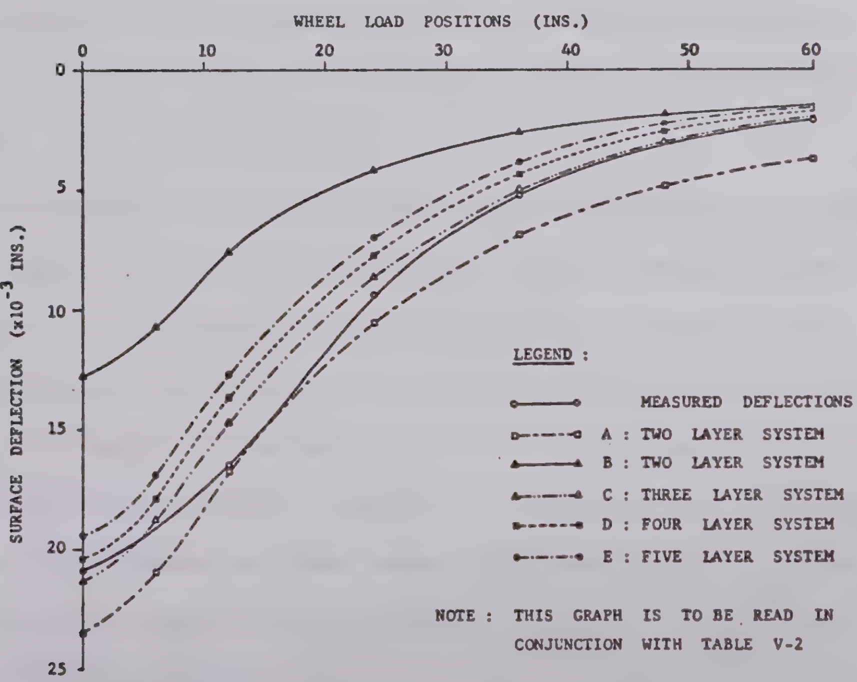


FIGURE 5.6. COMPUTED LONGITUDINAL DEFLECTION PROFILES FOR A SINGLE-LAYER PAVEMENT

shown in column (A) of TABLE V-2. In another case, a modulus value of 25,000 psi was assigned to the subgrade. This modulus value corresponds to a deviator stress of approximately 1.5 psi (FIGURE 5.4), which is likely to be expected in the subgrade at a depth of three feet. The computed center point stresses and deflections are shown in column (B) of TABLE V-2.

It is observed from the results presented in columns (A) and (B) of TABLE V-2 and the corresponding deflection profiles in FIGURE 5.6 that there is a great disparity in the stresses and deflections for the two cases. However, center point stresses and deflections in column (A) are closer to the measured parameters indicating that when a two-layered system is used for the structural analysis, the modulus value assigned to the subgrade must be in the region corresponding to the likely deviator stress in the subgrade at the pavement-subgrade interface.

In subsequent cases, the subgrade was divided into two, three and four layers with the last layer always being of semi-infinite thickness and the preceding layers adding up to a thickness of 66 inches, which is the thickness of compacted subgrade in the prototype pavement. The moduli values assigned to the various layers were taken from the experimental results (FIGURE 5.4) corresponding to the estimated deviator stresses in those layers. The center point stresses and deflections computed for these cases (C, D, and E) were in very close agreement with the measured values, the maximum variations being: a) 1.5×10^{-3} inches in deflection, which is about 7 percent, and b) 0.5 psi in stress, which is about 4 percent.

Examination of FIGURE 5.6 shows that deflection profiles corresponding to the cases in columns (A), (C), (D), and (E) of TABLE V-2, are similar in nature to the measured profile and they follow it very closely. The deflection profile for case (C), which is a three-layered system, has the closest agreement with the measured profile, the difference of deflection under the wheel being two and one half percent. The dividing of the subgrade into further layers causes the surface deflection to decrease, but the rate of decrease is moderate. In comparing with the measured deflection under the wheel, the deflection for a five-layered system (case E) is underestimated by seven percent while for a two-layered system (case A) it is overestimated by twelve percent, although all the computed deflection profiles are almost parallel to each other.

The results presented in TABLE V-2 and FIGURE 5.6 and their close agreement with the respective measured parameters is encouraging, and seems to justify the use of elastic layer theory for multi-layered pavement systems. However, it must be noted that the conclusion thus drawn is based on the utilization of pavement properties at the time of field measurement, and an assumed time of loading.

5.4.2. Two-Layer Pavement

Another analysis similar to the previous case was done. The asphalt concrete was divided into two layers instead of a single layer as in the previous case, and a reasonable temperature difference of 15°F between the top and bottom of the pavement was assumed. After several trials (TABLE V-7) to determine the appropriate loading time which will

be discussed later, a loading time of 0.5 seconds and the average temperature of each layer were used to determine the stiffness of each layer, while the modulus assigned to the subgrade was determined as in the previous case. The subgrade was divided to constitute a maximum of three layers.

The results of this analysis are shown in TABLE V-3 and FIGURE 5.7. The stresses and deflections obtained are almost identical with those obtained in the previous analysis. Since the subgrade moduli in both cases are in the same range, it is the stiffness of the asphalt concrete which influences the magnitude of stresses and deflections. Hence proper use of the stiffness values are of great importance for predicting stresses and deflections. If the asphalt concrete within the pavement has a uniform temperature, it can be treated as a single layer and the assignment of stiffness values is fairly simple. On the other hand if there is temperature variation within the asphalt concrete, attempts must be made to obtain the actual pavement stiffnesses. The behaviour of asphalt concrete is complex and its stiffness varies with time and temperature as noted by Van der Poel (1954). Under these circumstances obtaining actual stiffnesses is difficult and great care must be exercised in choosing the effecting parameters.

In this analysis it was found that a combination of loading time of 0.5 seconds and temperatures of 38°F and 30°F for the top and the bottom layer, respectively, is equivalent in terms of stiffness to a combination of a loading time of 0.1 seconds and a uniform temperature of 42°F throughout both the layers. These stiffnesses can be said to be

TABLE V-3

COMPUTED STRESSES AND DEFLECTIONS FOR A TWO-LAYER PAVEMENT

MILE 9.44, SURFACE TEMPERATURE 40°F, PAVEMENT THICKNESS 7.2 INS., LOADING TIME 0.5 SECONDS							
Layer Thickness ins.	Poisson's Ratio	Average Layer Temperature °F	Moduli and Stiffness of Pavement (psi) A	B	C	D	E
2.1	0.33	38.0	175000	175000	175000	175000	175000
5.1	0.33	30.0	380000	380000	380000	380000	380000
30.0	0.40	-	-	-	-	10000	10000
36.0	0.40	-	-	-	-	15000	20000
66.0	0.40	-	-	-	10000	-	-
Semi Infinite	0.50	-	10000	25000	25000	25000	25000
SURFACE DEFLECTION UNDER THE WHEEL (x 10^{-3} ins.)			23.1	12.5	21.0	20.0	19.4
VERTICAL STRESS ON SUBGRADE UNDER THE WHEEL (psi)			11.1	18.0	10.9	11.0	11.0

Measured parameters under the wheel : a) Surface Deflection : 20.9 x 10^{-3} ins.
b) Vertical Stress on Subgrade : 11.8 psi.

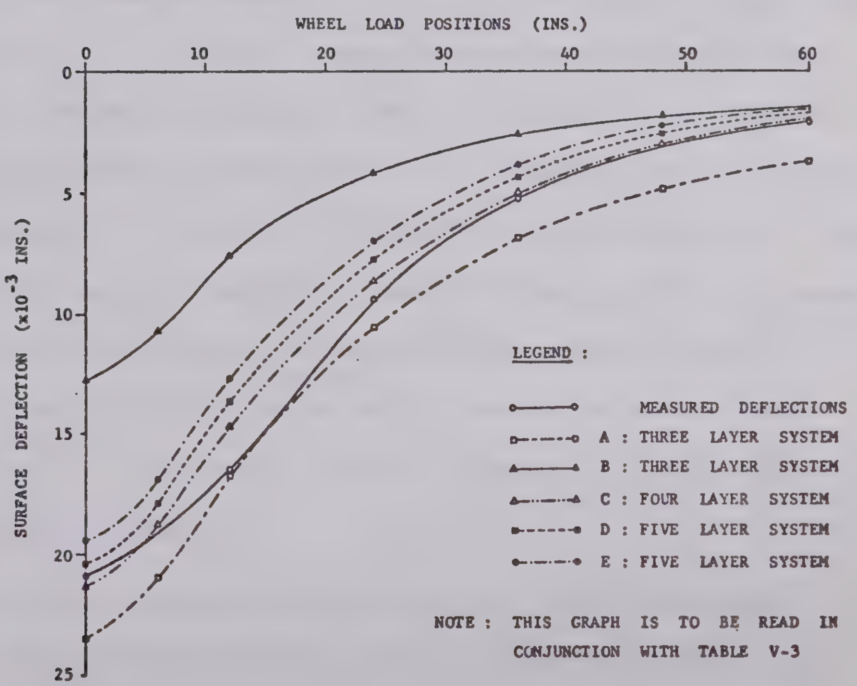


FIGURE 5.7. COMPUTED LONGITUDINAL DEFLECTION PROFILES FOR A TWO-LAYER PAVEMENT

appropriate representations in the pavement model since in both cases the stresses and deflections computed were in very close agreement with the measured values.

5.4.3. Variable Pavement Thickness

It has been seen earlier that division of the subgrade into two layers, one layer for the compacted subgrade and one layer for the undisturbed subgrade, produced results which were the closest in agreement with the measured parameters. Hence, structural analyses with a similar model were made for different asphalt concrete thicknesses for which measured stresses and deflections were available for comparison. The results of the analyses are presented in TABLES V-4, V-5 and V-6. It is seen that when the asphalt concrete is treated as a single layer as in the case for 5.5 inches pavement thickness, the stresses and deflections computed and shown in TABLE V-4 compare favourably with the measured values when a loading time of 0.1 seconds is used. When the asphalt concrete is treated as two layers as in the case for 9.3 inches pavement thickness, the computed parameters shown in TABLE V-5 compare favourably with the measured parameters when a loading time of 0.5 seconds is used. This phenomenon of 0.1 seconds for single-layer pavements and 0.5 seconds for two-layer pavements was also observed in the two previous analyses.

Computed stresses and deflections for a 5.1 inches thick pavement given in TABLE V-6 are not in precise agreement with the measured values. It is observed from the previous analyses that the temperature of asphalt concrete was low (in the region of 40°F) and the

TABLE V-4

COMPUTED STRESSES AND DEFLECTIONS FOR

5.5 INCHES THICK PAVEMENT

MILE: 11.00, SURFACE TEMPERATURE: 45°F, PAVEMENT THICKNESS: 5.5 INCHES								
Layer Thickness		Poisson's Ratio	Average Layer Temperature	Moduli and Stiffness at Loading Times (Secs.) of: (in psi)				
Layer No.	ins.		°F	0.10	0.20	0.30	0.40	0.50
1	5.5	0.33	43.0	250000	185000	155000	135000	121000
2	12.0	0.40	-	10000	10000	10000	10000	10000
3	Semi Infinite	0.50	-	25000	25000	25000	25000	25000
SURFACE DEFLECTION UNDER THE WHEEL (x 10^{-3} ins.)				21.6	24.1	25.6	26.9	28.0
VERTICAL STRESS ON SUBGRADE UNDER THE WHEEL (psi)				18.8	21.8	23.7	25.2	26.5

Measured parameters under the wheel : a) Surface Deflection : 22.5 x 10^{-3} ins.
b) Vertical Stress on Subgrade : 18.4 psi.

TABLE V-5

COMPUTED STRESSES AND DEFLECTIONS FOR

9.3 INCHES THICK PAVEMENT

MILE: 11.00, SURFACE TEMPERATURE: 40°F, PAVEMENT THICKNESS: 9.3 INCHES								
Layer Thickness		Poisson's Ratio	Average Layer Temperature	Moduli and Stiffness at Loading Times (Secs.) of: (in psi)				
Layer No.	ins.		°F	0.10	0.20	0.30	0.40	0.50
1	3.8	0.33	38.0	360000	260000	217000	190000	175000
2	5.5	0.33	37.0	380000	280000	230000	205000	185000
3	12.0	0.40	-	10000	10000	10000	10000	10000
4	Semi Infinite	0.50	-	25000	25000	25000	25000	25000
SURFACE DEFLECTION UNDER THE WHEEL (x 10^{-3} ins.)				11.7	13.3	14.5	15.3	15.9
VERTICAL STRESS ON SUBGRADE UNDER THE WHEEL (psi)				7.1	8.5	9.4	10.0	10.6

Measured parameters under the wheel : a) Surface Deflection : 16.5 x 10^{-3} ins.
b) Vertical Stress on Subgrade : 11.9 psi.

TABLE V-6

COMPUTED STRESSES AND DEFLECTIONS FOR 5.1 INCHES THICK PAVEMENT

MILE: 9.44, LOADING TIME: 0.1 SECONDS, PAVEMENT THICKNESS: 5.1 INCHES

Layer Thickness		Poisson's Ratio	Surface Temperature					
			$50^{o}F$		$60^{o}F$		$75^{o}F$	
Layer No.	ins.		Layer Stiffness psi	Average Layer Temperature ^{o}F	Layer Stiffness psi	Average Layer Temperature ^{o}F	Layer Stiffness psi	Average Layer Temperature ^{o}F
1	5.1	0.33	270000	42.0	153000	52.0	53000	67.0
2	66.0	0.40	10000	-	10000	-	10000	-
3	Semi-Infinite	0.50	25000	-	25000	-	25000	-
SURFACE DEFLECTION UNDER THE WHEEL (x 10^{-3} ins.)			28.8		34.4		47.0	
VERTICAL STRESS ON SUBGRADE UNDER THE WHEEL (psi)			18.9		25.0		38.7	

Measured parameters under the wheel : a) Surface Deflection : 25.5 x 10^{-3} ins.

b) Vertical Stress on Subgrade : 27.2 psi.

stiffnesses used in the analyses gave good predictions. But in this case, the temperature within the pavement varied from 75°F at the top to 60°F at the bottom, which could be a possible reason for the predicted values to be inconsistent with the measured values.

The asphalt used in the prototype pavement was of a low viscosity and high penetration grade, with a penetration index of -1.0 indicating that this asphalt is highly temperature susceptible. This type of asphalt is known to exhibit a complex behaviour at high temperatures (Kopvillem and Heukelom, 1969), thereby resulting in a possible erroneous determination of the mixture stiffness at 75°F. As discussed in section 5.2, the concept of shift factor as observed by Finn (1967) is only applicable to materials exhibiting thermorheologically simple behaviour. As such, the shift factor used for determining the stiffness at higher temperature was physically possible from FIGURE 5.2, but the actual effect was not known. When using the concept of shift factor, one should be aware of its possible limitations and the range of its applicability.

5.4.4. Variation in Loading Time

The effect of variation of loading time from 0.1 to 10.0 seconds on the computed stresses and deflections was investigated and the results are tabulated in TABLE V-7. The subgrade was treated as two layers and the asphalt pavement as two layers. The subgrade moduli were kept constant and the pavement stiffness varied with loading time. It was observed from the results that with this increase in loading time, the computed stresses increased approximately three-fold and the

TABLE V-7

EFFECT OF LOADING TIME ON COMPUTED STRESSES AND DEFLECTIONS

MILE 9.44, SURFACE TEMPERATURE 40°F, PAVEMENT THICKNESS : 7.2 INCHES

Layer No.	Layer Thickness (ins.)	Poisson's Ratio	Average Layer Temperature (°F)	Moduli and Stiffness at Loading Times (in Seconds) of : (in psi) 0.10	0.20	0.25	0.30	0.50	0.70	0.80	0.90	1.00
1	2.1	0.33	38.0	355000	260000	235000	217000	175000	148000	148000	130000	123000
2	5.1	0.33	30.0	740000	570000	520000	480000	380000	335000	310000	300000	278000
3	66.0	0.40	-	10000	10000	10000	10000	10000	10000	10000	10000	10000
4	Semi-Infinite	0.50	-	25000	25000	25000	25000	25000	25000	25000	25000	25000
SURFACE DEFLECTION UNDER THE WHEEL (x 10^{-3} ins.)				16.2	18.1	18.7	19.3	21.0	22.1	22.7	23.0	23.6
VERTICAL STRESS ON SUBGRADE UNDER THE WHEEL (psi)				7.3	8.6	9.1	9.6	10.9	11.8	12.3	12.5	13.0
				Moduli and Stiffness at Loading Times (in Seconds) of : (in psi) 2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
1	2.1	0.33	38.0	87000	72000	61000	56000	49000	45000	42000	40000	37500
2	5.1	0.33	30.0	205000	170000	150000	135000	122000	113000	107000	100000	96000
3	66.0	0.40	-	10000	10000	10000	10000	10000	10000	10000	10000	10000
4	Semi-Infinite	0.50	-	25000	25000	25000	25000	25000	25000	25000	25000	25000
SURFACE DEFLECTION UNDER THE WHEEL (x 10^{-3} ins.)				26.5	28.4	29.8	30.9	32.2	33.2	33.9	34.7	35.3
VERTICAL STRESS ON SUBGRADE UNDER THE WHEEL (psi)				15.4	17.0	18.2	19.1	20.2	20.9	21.5	22.1	22.6

Measured parameters under the wheel : a) Surface Deflection : 20.9 x 10^{-3} ins.

b) Vertical Stress on Subgrade : 11.8 psi.

deflections increased approximately two and one half times over the whole range under consideration, the rate of increase for each increment of loading time being moderate.

It was also observed from this analysis that when the pavement was treated as two layers with a temperature variation within it, a 0.1 seconds loading time no longer predicted precise pavement responses as in the case for a single-layer pavement. These trials indicate that a loading time of 0.5 seconds with the combinations of temperatures considered in each pavement layer gives an appropriate stiffness, which when used in the pavement model predicts reasonable stresses and deflections. The trials in this analysis are the basis of selecting the loading time for the analysis in section 5.4.2.

5.4.5. Variation in Temperature

Initially, a hypothetical pavement section was chosen to formulate a pavement model to see the effects of variations in a) pavement temperature from 40°F to 70°F, and b) the thickness and moduli of compacted subgrade, on computed stresses and deflections. The results of these analyses are tabulated in TABLE V-8. The pavement model consisted of three asphalt concrete layers having a total temperature variation of 15°F between the surface and the bottom of the asphalt concrete pavement. The subgrade was divided into two layers, one for the compacted subgrade and one for the undisturbed subgrade. The loading time was kept constant at 0.1 seconds and the stiffness varied with temperature. At a particular temperature, the pavement stiffness was kept constant and the compacted subgrade modulus was varied while

TABLE V-8

EFFECT OF TEMPERATURE ON COMPUTED STRESSES AND DEFLECTIONS

TRIAL SECTION, LOADING TIME: 0.1 SECONDS, PAVEMENT THICKNESS: 8.0 INCHES

Layer Thickness		Poisson's Ratio	Surface Temperature												
			40°F			50°F			60°F			70°F		
Layer No.	ins.		Layer Stiffness psi	Average Layer Temperature °F		Layer Stiffness psi	Average Layer Temperature °F		Layer Stiffness psi	Average Layer Temperature °F		Layer Stiffness psi	Average Layer Temperature °F	
First Trial : 66 inches of compacted Subgrade														
1 2 3	2.0 3.0 3.0	0.33 0.33 0.33	360000 530000 940000	38.0 33.5 28.0		195000 245000 360000	48.0 43.5 38.0		117000 149000 195000	58.0 53.5 48.0		49000 78000 117000	68.0 63.5 58.0	
4 5	66.0 Semi Infinite	0.40 0.50	6000 25000	8000 25000	10000 25000	6000 25000	8000 25000	10000 25000	6000 25000	8000 25000	10000 25000	6000 25000	8000 25000	10000 25000
SURFACE DEFLECTION UNDER THE WHEEL (x 10^{-3} ins.)			17.7	15.7	14.3	25.2	21.9	19.6	31.6	27.2	-	41.4	35.5	31.5
VERTICAL STRESS ON SUBGRADE UNDER THE WHEEL (psi)			4.3	5.2	6.0	7.1	8.5	9.7	9.9	11.6	-	14.2	16.5	18.5
Second Trial : 24 inches of compacted Subgrade														
1 2 3	2.0 3.0 3.0	0.33 0.33 0.33	360000 530000 940000	38.0 33.5 28.0		195000 245000 360000	48.0 43.5 38.0		117000 149000 195000	58.0 53.5 48.0		49000 78000 117000	68.0 63.5 58.0	
4 5	24.0 Semi Infinite	0.40 0.50	6000 25000	8000 25000	10000 25000	6000 25000	8000 25000	10000 25000	6000 25000	8000 25000	10000 25000	6000 25000	8000 25000	10000 25000
SURFACE DEFLECTION UNDER THE WHEEL (x 10^{-3} ins.)			14.5	13.2	12.4	20.7	18.6	17.1	26.3	23.4	21.4	35.1	31.1	28.4
VERTICAL STRESS ON SUBGRADE UNDER THE WHEEL (psi)			4.8	5.6	6.3	7.6	8.9	10.0	10.3	12.0	13.5	14.6	16.8	18.7

the modulus of the undisturbed subgrade was maintained at 25,000 psi. The first trial incorporated a compacted subgrade thickness of 66 inches and the second trial incorporated a compacted thickness of 24 inches.

It was observed from the results of this analysis that as the pavement temperature increased, thereby decreasing the pavement stiffness, the computed stresses and deflections also increased. At a particular temperature and subgrade modulus, the decrease in subgrade thickness resulted in a decrease in deflection and an increase in stress. Also, at the same temperature and subgrade thickness, an increase in the subgrade modulus resulted in a decrease in deflection and an increase in stress. This is what would be naturally expected because an increase in modulus means a stiffer material and hence it is likely to undergo less deformation.

It can be concluded from this analysis that at higher temperatures (70°F), the thickness and moduli of the compacted subgrade have considerable effect on the computed stresses and deflections, while at low temperatures (40°F) the effects are moderate. The increase in temperature increases the computed pavement responses, the stresses increasing approximately three-fold and the deflections increasing approximately two and one half times over the whole range of temperature (40°F to 70°F), the rate of increase between the increment of 60°F and 70°F being quite pronounced.

5.5. Summary

The major observations in this chapter can be summarized as:

1) The resilient modulus of a clayey soil does not change significantly after 5,000 stress applications, when the samples are tested immediately after their preparation.

2) The rate of decrease in the resilient modulus was very pronounced in the low deviator stress range, and it was low in the higher range of deviator stress.

3) The resilient modulus versus deviator stress curve shifts to a lower order of resilient modulus when the moisture content in the soil is increased beyond optimum.

4) The foot penetration of the kneading compactor affects the resilience of clayey soils.

5) A sample can be tested several times, under repeated loading, to produce compatible results provided the applied stress, the resulting strain and the number of load repetitions are low.

6) When proper material properties are incorporated in the Chevron 5-layered elastic theory computer program, reasonably good prediction of pavement responses are obtained.

7) When the subgrade is divided into two layers, one representing the compacted subgrade and one representing the

undisturbed subgrade soil, and the modulus for each layer is assigned from the laboratory tests, best correlation between the predicted and measured deflections are obtained.

8) The behaviour of asphalt concrete is very sensitive to the temperature and loading time and care must be taken in considering these factors when stiffnesses are determined.

The subgrade moduli obtained from the field static test using the deflection bowl analysis and presented in TABLE III-1, are within the range of the resilient moduli determined in the laboratory for the same material. This provides some confidence in using the deflection bowl analysis to arrive at the subgrade moduli, and either method could be used to yield reasonable results.

CHAPTER VI

PRACTICAL IMPLICATIONS

6.1. General

The previous chapter indicated that when proper pavement materials properties were used in the 5-layered elastic theory, reasonably good predictions of pavement deflections and stresses were obtained. The asphalt concrete stiffness was very sensitive to temperature and loading time. This latter parameter is difficult to assess, however, if several full-depth sections for which data are available for comparison are analysed at a particular temperature, the loading time can be deduced with reasonable accuracy.

The elastic theory for multi-layered pavement systems may be useful in developing design curves for full-depth asphalt pavements. A detailed investigation in this aspect was not undertaken, but a procedure illustrating the development of a method and possible use is outlined.

6.2. Tolerable Deflections

Many studies in the past have been made to relate pavement deflection with performance and future traffic use, the major findings of which have been summarized by Kingham (1969). He has compiled a traffic-deflection relationship shown in FIGURE 6.1, from the experience

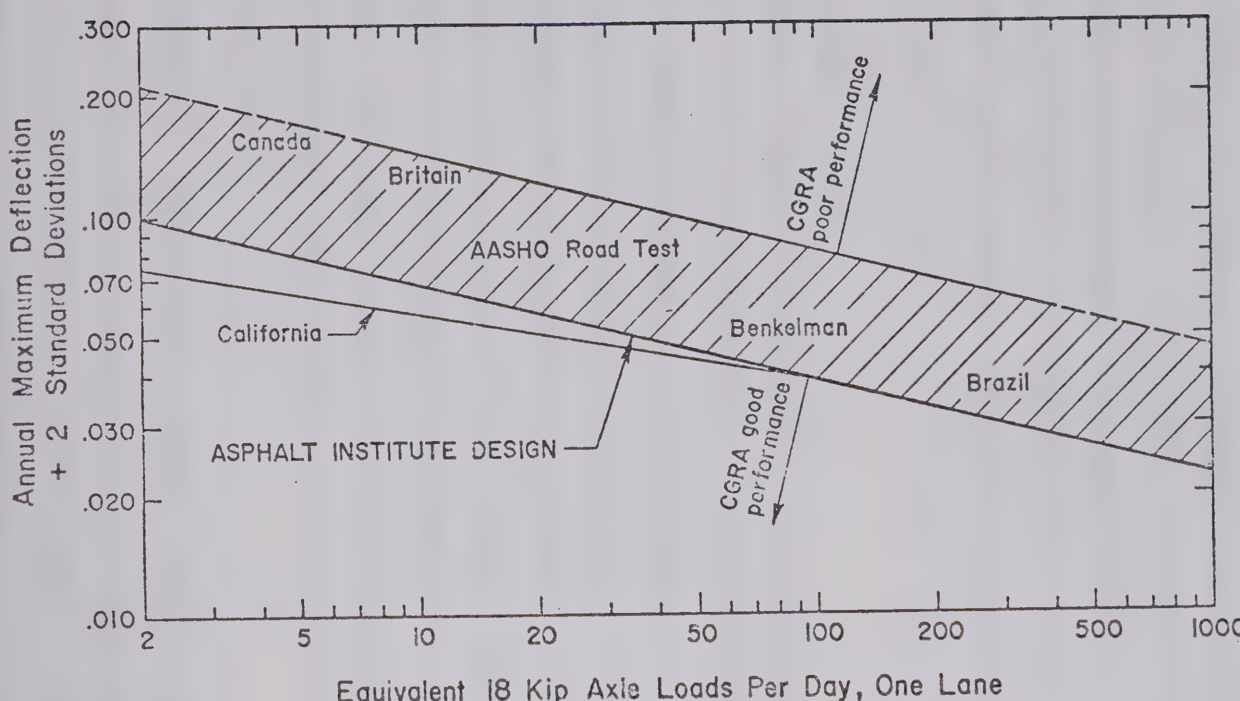


FIGURE 6.1 - COMPILATION OF BEAM DEFLECTION EXPERIENCE
(After Kingham, 1969)

of various agencies in different countries. The Asphalt Institute has adopted a Design Line which is considered to represent a conservative relationship in that the probability of an unsatisfactory design is very low. Detailed investigation into this aspect of the problem was not undertaken because it is considered to be a study by itself. However, the consideration of the Asphalt Institute's Design Line for use with the design curves suggested here was checked with the data available in this investigation.

6.3. Design Curves

It has been indicated in the previous section that a guide such as the Design Line of the Asphalt Institute is available to relate pavement deflection with performance and future traffic use. This information can be effectively used for design purposes if a relation between the pavement deflection and pavement thickness can be established. The Chevron 5-layered elastic theory computer program which computed pavement deflections that agreed reasonably well with the measured values in this investigation, can be used for this purpose. A procedure for developing design curves using this computer program is outlined in this section.

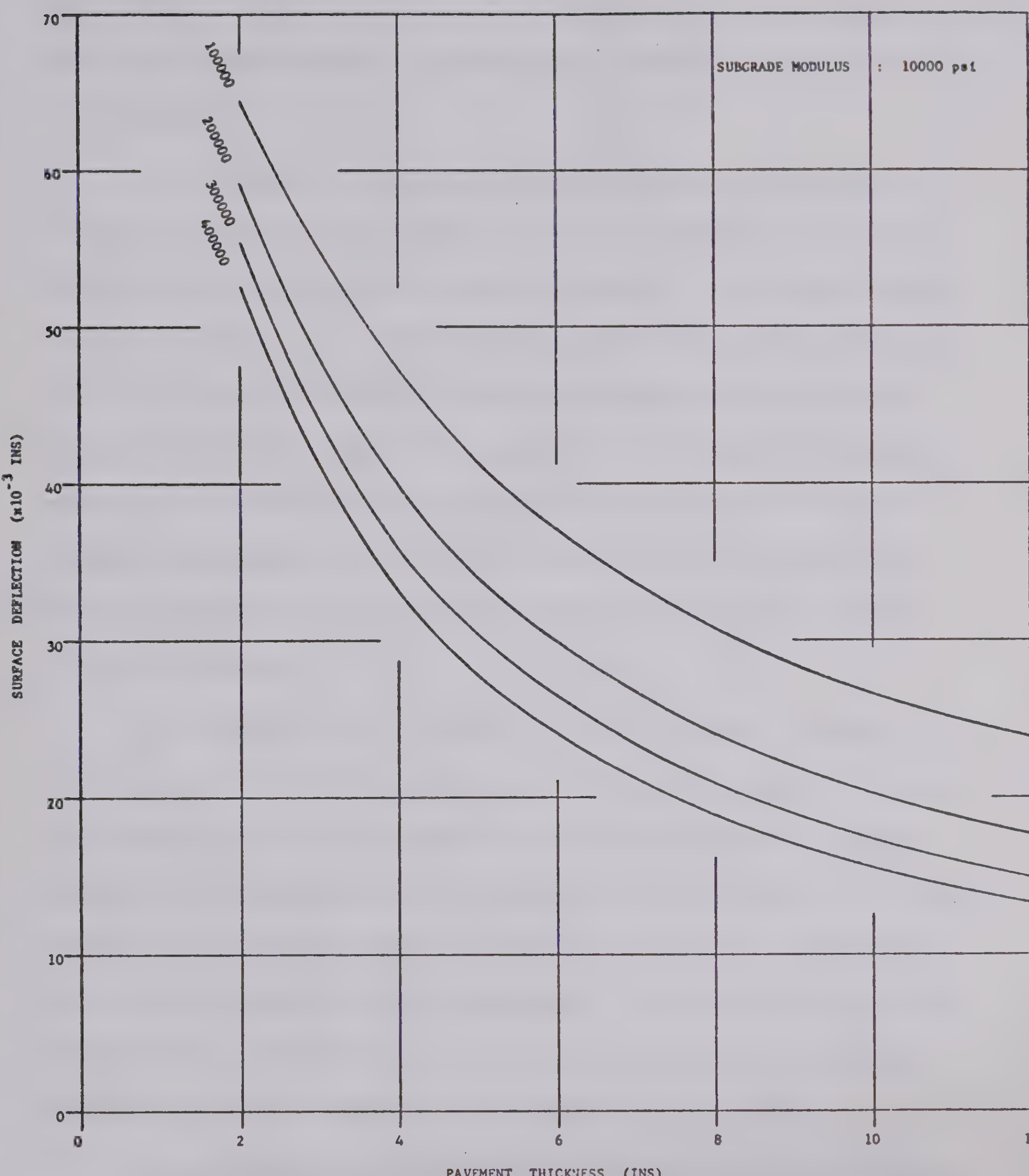
For simplicity in developing the design curves, a two-layered pavement model with one layer of asphalt concrete and one layer of subgrade, is used here for illustration. If more accuracy is desired two layers of subgrade (one for compacted subgrade and one for undisturbed subgrade) can be used in the pavement model to be incorporated in the computer program.

Initially, for a particular subgrade modulus and asphalt concrete stiffness, the Chevron 5-layered elastic theory computer program is used to compute the surface deflections of the pavement for asphalt concrete thicknesses in increments of two inches. Without altering the subgrade modulus, asphalt concrete stiffness is changed to the next value and pavement deflections are computed for the range of asphalt concrete thicknesses used in the previous case. This process is repeated for the entire range of pertinent asphalt concrete stiffnesses.

The surface deflections of the pavement computed for different asphalt concrete thicknesses and stiffnesses at that particular subgrade modulus, are plotted in a relationship of surface deflection versus pavement thickness. This will result in curves for a particular stiffness extending over the range of asphalt concrete thicknesses used. A typical plot of this nature for a subgrade modulus of 10,000 psi is shown in FIGURE 6.2. Similar curves are obtained for each different subgrade modulus in the range of the appropriate subgrade moduli.

6.4. Use of Design Curves

One of the current criterion for the design of pavements and overlays is to keep the peak pavement deflections within certain tolerable limits (Kingham, 1969). It has been seen in section 6.2 that maximum tolerable deflections of a pavement can be selected from the experience of various agencies in different countries, by knowing the volume of traffic the pavement section is expected to carry. The subgrade is the weakest in spring and peak deflections of pavements are



NOTE : Pavement Stiffness (in psi) is indicated on the curve.

FIGURE 6.2 - DEFLECTION-THICKNESS-MODULI RELATIONSHIPS FOR FULL-DEPTH ASPHALT PAVEMENT STRUCTURES

most likely to be obtained at that time; hence, the spring environmental conditions should be used in choosing the pavement materials properties and responses.

The maximum tolerable deflection the pavement is allowed to undergo is selected from FIGURE 6.1, using the Asphalt Institute's Design Line and the expected volume of traffic. The subgrade modulus for spring conditions is obtained and a set of design curves similar to the one shown in FIGURE 6.2, but corresponding to the determined subgrade modulus is chosen. The value of the tolerable deflection is entered in the deflection axis and is followed horizontally to the estimated spring pavement stiffness curve (interpolation may be required) from where the corresponding thickness of asphalt concrete pavement is obtained.

This technique of determining asphalt concrete thickness may also be used for the design of overlays of existing pavement structures by formulating a suitable pavement model to be used in the computer program. The pavement model thus formulated can be checked by comparison with a few measured Benkleman Beam deflections and corrections to the model if necessary can be implemented. For a desired deflection, the difference between the thickness thus obtained and the existing thickness of asphalt concrete is the thickness of overlay.

The consideration of the Asphalt Institute's Design Line for use with the design curves suggested here was checked with the data available in this investigation. It was found that when working back from the design curve (FIGURE 6.2) using the materials properties in the

fall and converting the fall deflection to the peak deflection in spring (by multiplying the fall deflection by 1.8, as observed by Kingham), the Design Traffic Number arrived at was approximately sixty-five. This, according to the Asphalt Institute's (1969) traffic classification represents medium traffic, which is reasonable for the highway under study in this investigation. Hence, the Asphalt Institute's Design Line is reasonable for consideration in obtaining tolerable deflections for use in the design method suggested here.

Considering practical aspects such as variations during construction and the capability of construction equipment, it would seem reasonable that the thickness be rounded off to the next half inch. If such is to be the case, a two-layered pavement model is considered sufficiently accurate to estimate the required thickness.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

The main purpose of this thesis was to investigate the effectiveness of the elastic theory for layered systems in predicting pavement responses. The conclusions reached from this investigation were drawn from the repeated loading triaxial test program, the analyses of data using the Chevron 5-layered computer program and the literature review. The conclusions presented are limited by the scope of the testing program and availability of data for comparison. The pavement under study was a full-depth asphalt concrete pavement, hence the findings of this investigation can be only applied to that type of pavement.

a) The conclusions drawn from the review of literature are as follows:

   1) A proper description of the behaviour of pavement materials under repeated loads is indispensible for successful application of the elastic theory for layered systems. For this purpose, the resilient modulus is found satisfactorily to represent the elastic modulus of the pavement materials for use in computations.

2) Kneading compaction produces laboratory specimens with resilient characteristics similar to those observed in the field specimens.

3) Asphalt concrete stiffness can be determined by the use of nomographic procedures based on the recovered properties of asphalt concrete.

b) The conclusions made from the results of the testing program on the subgrade soil are:

1) The determination of the resilient modulus at 5,000 stress applications when samples are tested immediately after their preparation in the laboratory, and using a sample several times under different test conditions provided the applied stress, the resulting strain and the number of load applications are kept low, has been found to be a satisfactory procedure in this investigation.

2) The effect of stress intensity on the resilient modulus of clays is such that the rate of decrease in the resilient modulus is very pronounced in the low deviator stress range and it is almost constant in the higher range of deviator stress; and the curve as a whole shifts to a lower order of resilient modulus when the moisture content is increased beyond the optimum.

3) The foot penetration of the kneading compactor affects the resilience of clays.

c) It is concluded from the analyses that,

1) When the subgrade is divided into two layers, one representing the compacted subgrade and one representing the undisturbed subgrade, and the modulus for each layer is assigned from laboratory tests, the Chevron 5-layered elastic theory computer program computes stresses and deflections which are in very close agreement with the measured values.

2) The behaviour of asphalt concrete is very sensitive to the temperature and loading time and care must be taken in considering these factors when stiffnesses are determined.

3) From the construction point of view, a two-layer pavement model incorporated in the Chevron 5-layered computer program is sufficiently accurate for the design of full-depth asphalt pavements and overlays.

7.2. Recommendations

a) The apparatus used in this investigation performed satisfactorily and gave excellent results. However, the electrical timing unit sometimes failed to operate during the test and its replacement is desirable. The timing unit has another disadvantage in that it can give a minimum on-load time of 0.25 seconds, which represents the loading time of a vehicle travelling at approximately 15 miles per hour. When the timing unit is being replaced, it would be advantageous to have some extra features

included in the new one. It is recommended that the new timing unit have the capability of,

1) Achieving the on-load times of vehicles travelling at high speed.

2) Simulating the loading sequence of multiple axle vehicles.

3) Operating continuously during the test for any number of load applications.

b) It was found in this investigation and from available literature that the foot penetration of a kneading compactor affects the resilient modulus of clayey soils. It was also observed from the literature review that kneading compaction produced laboratory samples with similar resilience characteristics as those in field samples. In view of the importance of kneading compaction, a detailed investigation into the effect of foot penetration on the resilience of different types of soils would prove useful for future works.

c) Most highways are using treated bases for their construction. An investigation similar in nature to that in this thesis, could be carried out for different types of treated bases.

d) The procedure for obtaining design curves arrived at in this thesis, should be checked with more of the existing full-depth asphalt pavements to strengthen its validity.

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LIST OF REFERENCES

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APPENDIX A

REPEATED LOADING TRIAXIAL TEST APPARATUS

A.1. Description

The repeated loading triaxial test apparatus set up at the University of Alberta is modelled after the one developed by Seed and Fead in California. FIGURE A.1 shows the layout of the apparatus. The essential features and the functions of the various components are described in this section. FIGURE A.1 should be referred to for corresponding alphabetic letters.

A Counterbalance for Loading Yoke. As the name implies, it is a weight used to counterbalance the effect of the weight of the loading yoke on the piston and ram.

B Load Cell. A device for measuring the deviator stress applied to the specimen. This replaces the conventional proving ring, because of its ability to be used with the electrical recording system. Operating range : 0 to 2,000 lbs.

C LVDT. Linear variable differential transformer, commonly known as LVDT, is a displacement transducer operated electrically for measuring the deformation of a sample. Here it is used to measure the axial deformation of the sample external to the cell D. The LVDTs used here are Hewlett Packard displacement transducers, model 7DCDT-1000. Displacement range : ± 1.000 inch (full scale).

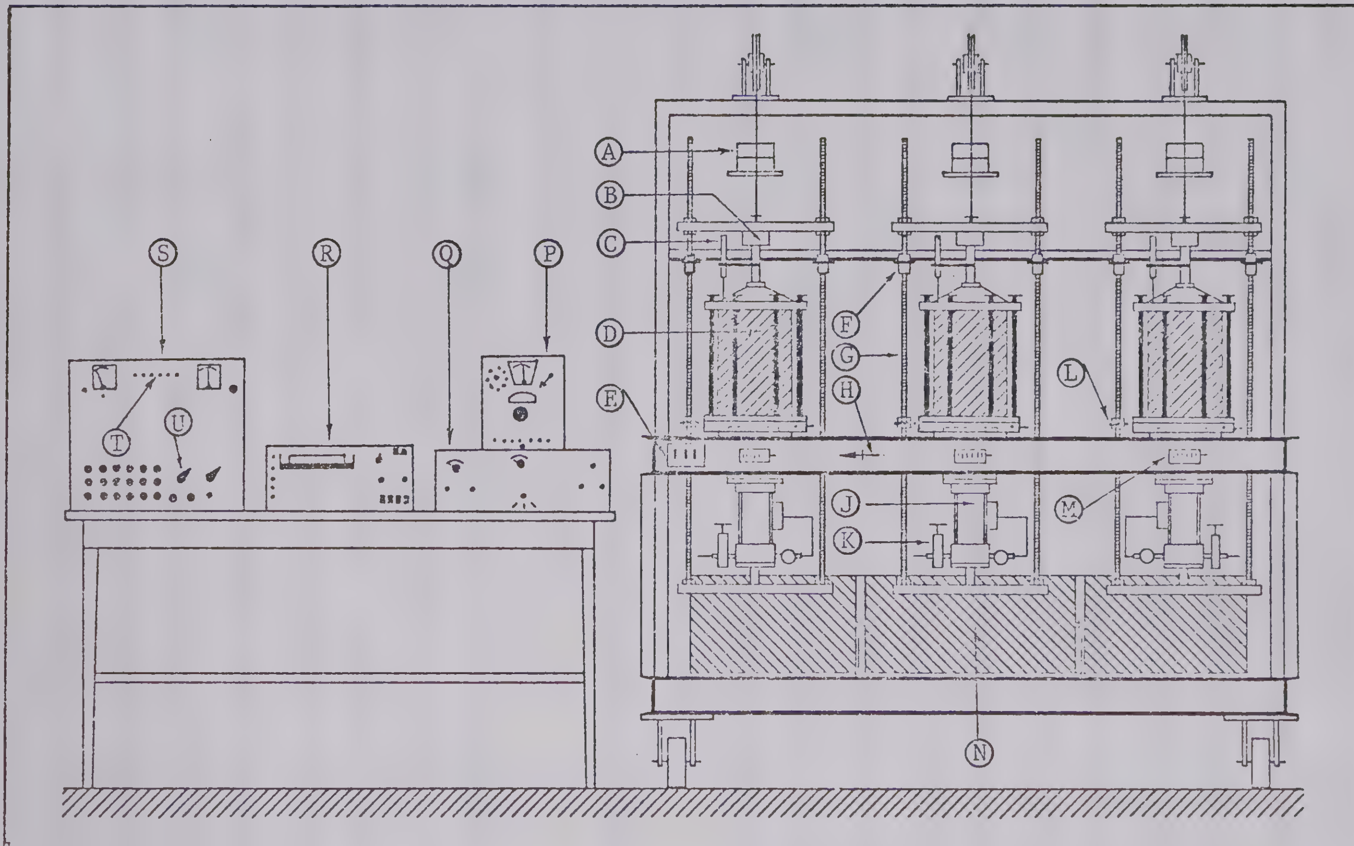


FIGURE A.1 - EQUIPMENT FOR TESTING SPECIMENS UNDER REPEATED AXIAL STRESS

D Triaxial Cell. This triaxial cell is of a standard size for testing 4 inch diameter and 8 inch high cylindrical samples. The base is supported by a platform in the testing machine frame, only over its central area so that the loading yoke can pass by the base without obstruction. The removable cylinder is of a 0.375 inch thick perspex. Because of the butt joint in the perspex, which is the source of weakness, four circumferential bands of one inch width and 0.1 inch thick and made of resin-bonded glass fiber, are fixed on the outside of the cylinder as reinforcements. The loading ram is a 0.75 inch diameter ground stainless-steel rod, which is fitted with a collar and a hemi-spherical piece. The features of the triaxial cell are shown later in this section. Capacity : Loading ram - 6,000 lbs. axial load,

Cell - 150 psi.

E Bay Operation Switches. These switches when switched on, start the operation of the respective bays.

F Guide Frame for Loading Yoke. This unit consists of a plate with a slot bolted to the frame, and an annular cylinder threaded in the inside and smooth outside. The cylinder is screwed to one arm of the loading yoke and is made to pass through the slot of the plate. Such a unit is installed on each arm of the loading yoke. The purpose of this unit is to restrict the movement of the loading yoke to a vertical direction thereby insuring that the load applied to the load cell is vertical. This unit thus helps in preventing the load cell from being damaged.

G <u>Loading Yoke</u>. A rectangular frame, connected to the piston at the bottom and to the loading ram of the triaxial cell through the load cell at the top. It transfers the load from the piston to the loading ram.

H <u>Pressure Transducer with Three-Way Valve Switch</u>. The pressure transducer is a very sensitive gauge. It is used here to measure the confining pressure in three triaxial cells. (A single transducer is used to measure the confining pressures of three cells, individually.) This is achieved by using a four-way valve in which the pressure transducer is connected to one of the arms while the other three arms are connected to the three triaxial cells. By using a three-way valve switch, the pressure from two triaxial cells is shut off and the pressure from the third triaxial cell is measured by the transducer. Capacity : 300 psi (range, 0 to 300 psi) for transducer No. 28749.

J <u>Air-Pressure Cylinder and Piston</u>. This unit transfers the air pressure from the air-pressure reservoir tank to the loading yoke, in a mechanical form. The ones used here are : Hannifin Series 2A, Style HB (NFPA Style MF 6) with 4 inch diameter bore and LB+Stroke = 4.875 inches; Rod and Thread - KK, Style 4 and 9 (0.75 inch - 16).

K <u>Air-Pressure Regulators</u>. These units are installed at various tappings on the air-pressure reservoir tank for supply of air pressure to the triaxial cells. These units regulate the air pressure to the triaxial cells. Capacity : 125 psi maximum operating pressure.

L Safety Microswitches. These switches are installed on the frame close to one arm of the loading yoke, for each bay. A steel bar is sandwiched between two nuts and is mounted on the arm of the loading yoke nearest to the microswitch. The position of the steel bar on the arm of the loading yoke can be adjusted by rotating the nut on which the steel bar is mounted, thereby adjusting the gap between the switch and the steel bar.

The maximum axial deformation of the sample is estimated and the position of the steel bar is adjusted accordingly. In case there is a failure of the sample, the steel bar will come down and hit the microswitch. This will cut off further operation of that bay. Hence, damage to the apparatus is avoided.

M Counter. This is a six-digit resettable electrical counter, which is connected to the solenoid valve, and records the number of load applications on the specimen.

N Air-Pressure Reservoir Tank. This is a cylindrical tank which stores compressed air under pressure. The pressure requirements for the three triaxial cells can be supplied by this single tank. Capacity : 125 psi maximum pressure.

P Strain Indicator. This reads the strain from the pressure transducer. It is calibrated for the pressure range of the transducer, making it possible to read confining pressures. The strain indicator used here is a SR4 Strain Indicator No. 1721A.

Q Electrical Timing Unit. This unit consists of an electrical network of resistors, capacitors and inductance coils, which act as a pulsating unit. By adjusting the properties of the components of the network, the frequency and duration of loading can be controlled as desired. Minimum on-load time : 0.25 seconds.

R Ultra-Violet Recorder. This is a six channel unit. The movement of the ultra-violet beam is controlled by the movement of the galvanometer. There are six beams each corresponding to one LVDT or one load cell on one of the triaxial cells. The recording paper is a treated paper which is sensitive to ultra-violet light. The speed of the recording paper can be controlled. The one used here is manufactured by SE Laboratories, England, model : UV Recorder 3006.

S Galvanometer and Signal Conditioner Unit. This is also a six channel unit which takes in signals from the load cells and LVDTs, conditions them for the recorder and then passes them on to the ultra-violet recorder. The unit used here is : B&F Instruments, Inc. - Transducer Conditioner - model 6-101B1-10-200.

T Galvanometer Switches. These switches switch on the galvanometer to the various channels. By switching off a particular channel, the galvanometer in that channel and consequently the operation of the ultra-violet beam for that channel, is cut off. The panel used here is : B&F Instruments, Inc. - Meter and Switch Panel model SA364.

U Channel Selector Switch. This switches on the desired channel of the six channels so as to read the excitation voltage for the load cell or the LVDT. While it is switched on to a particular

channel, the load cell or the LVDT in that channel can be balanced to their null point.

Solenoid Valve (Not shown in the figure). This valve controls the flow of pressurized air from the air-pressure reservoir to the air-pressure cylinder and piston unit. It also acts as an exhaust for the air from the air-pressure cylinder and piston unit. This is a solenoid-operated three-way valve, the opening and closing of which is done electrically and is controlled by an electrical timing unit. The ones used here are : Hannifin - model CCJ 1-37. Range : 0 to 120 psi.

Air-Pressure Gauges (Not shown in the figure). These gauges are installed after the air-pressure regulators and indicate the air pressure being supplied by that particular pipe. These are inaccurate at low pressures (0 - 10 psi). Ranges: 0 to 60 psi and 0 to 160 psi.

FIGURE A.2 shows the principal features of the triaxial cell along with a typical specimen set up within it. FIGURE A.2 should be referred to for corresponding numbers.

1 stainless-steel loading ram, 0.75 inch in diameter

2 air release valve

3 rubber O-rings

4 0.5 inch diameter stainless-steel tie bars, 6 equally spaced

5 end cover plates (4 inch diameter x 0.25 inch thick metallic discs, for 8 inch high samples)

6 drainage and pore pressure connection

7 base of the triaxial cell

8 connection to pressure supply (for confining pressure)

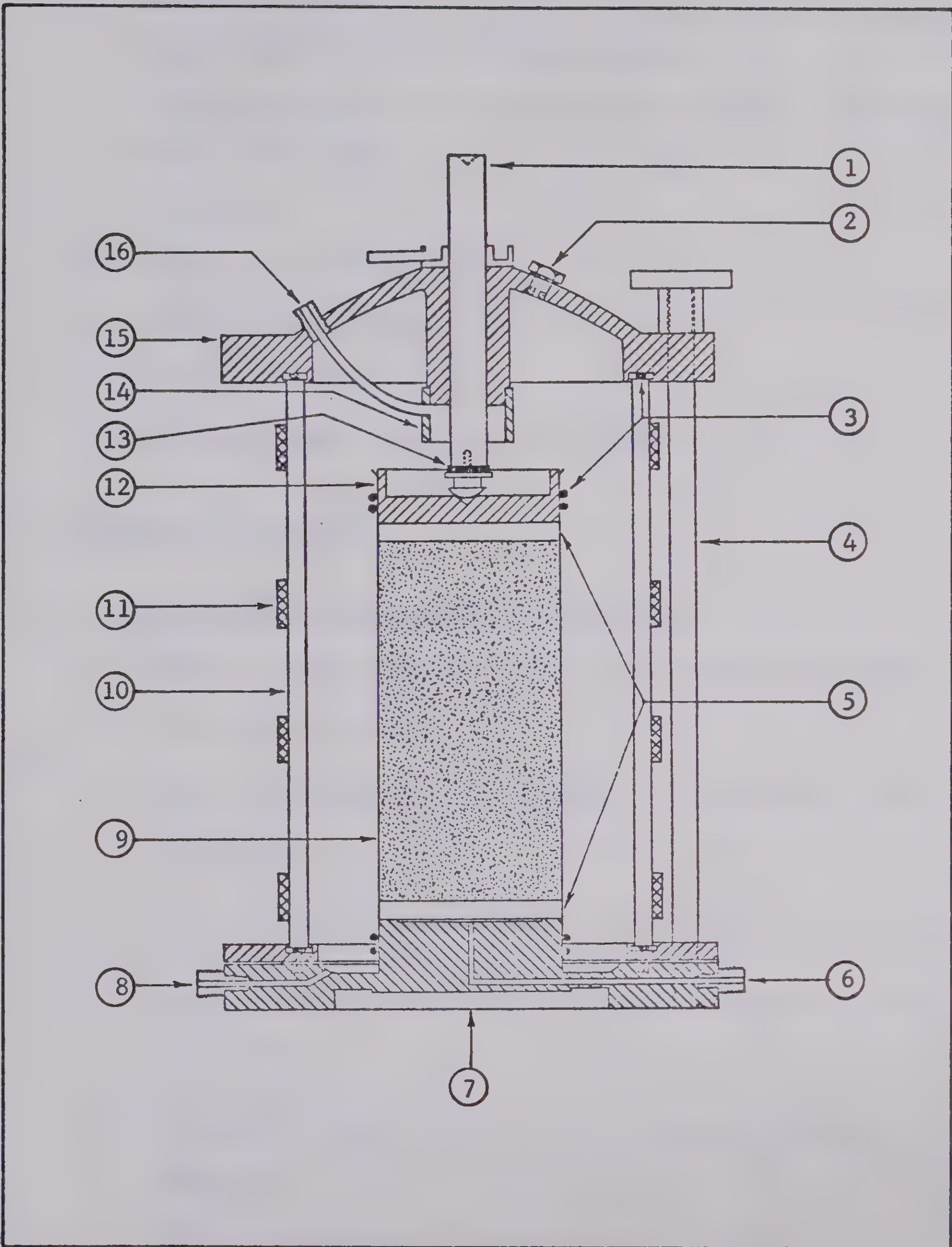


FIGURE A.2 - THE TRIAXIAL CELL (FOR 4 INCH DIAMETER SAMPLES)

9 4 inch diameter sample enclosed in two rubber membranes

10 perspex cylinder, 7.75 inches outer diameter, 7.0 inches inner diameter and 11.375 inches long

11 reinforcing bands of resin bonded glass fiber, 1 inch wide and 0.1 inch thick

12 loading cap

13 collar and pressure seal

14 perspex oil retainer

15 top cap of triaxial cell

16 polythene tube connection to oil supply.

A.2. Operational Procedure

A.2.1. Setting up the Sample in the Triaxial Cell

1) Place a 4 inch diameter cover plate on the seat in the base of the triaxial cell.

2) Place the sample (4 inch diameter x 8 inch high) on the cover plate.

3) Place a 4 inch diameter cover plate on top of the sample.

4) Place the loading cap, with the slot facing up, on the cover plate.

5) Enclose the sample with two 4 inch diameter rubber membranes.

6) Align the assembly for verticality.

7) Check and see that there are no kinks at the junctions of,

a) the triaxial base seat and the cover plate,

b) the cover plates and the sample,

c) the cover plate and the loading cap.

8) Fix two O-rings, over the rubber membranes to,

a) the triaxial base seat at the bottom,

b) the loading cap at the top.

9) Fold the excess of rubber membranes around the O-rings, neatly over the O-rings.

10) Mount the perspex encasing on the base of the triaxial cell, and give the mounting screws a few turns.

11) Check the eccentricity of the loading cap. This is done by lowering the loading ram into the slot of the loading cap and rotating the ram. If there is no lateral movement of the loading cap then there is no eccentricity. But if there is a lateral movement of the loading cap, then eccentricity is present. In this case the perspex encasing is removed and the sample and the loading cap are realigned. This process is repeated till there is no eccentricity present.

12) The mounting screws are tightened.

13) Close all the connection valves in the base of the triaxial cell.

14) Connect the distilled water supply pipe to the lateral pressure supply connection in the triaxial cell.

15) Open the lateral pressure supply connection valve and the air release valve and supply distilled water to the cell.

16) Allow the distilled water to rise to the level of the perspex oil retainer.

17) Shut the distilled water supply.

18) Pump oil through the polythene tube to the perspex oil retainer until the oil surrounds the loading ram.

19) Resume the distilled water supply and fill the cell.

20) Shut the lateral pressure supply connection valve and the air release valve.

21) Disconnect the distilled water supply pipe.

22) The triaxial cell is now ready to be placed in the loading bay.

A.2.2. Preparation of Bays for Testing

1) Close the bleeding valve of the air-pressure reservoir.

2) Fill the air-pressure reservoir tank with compressed air from the air-pressure line of the building, by opening the air-pressure valve.

3) Switch on the,

   a) Galvanometer and Signal Conditioner unit. (Transducer Conditioner unit.)

   b) Electrical timing unit.

   c) Ultra-Violet recorder.

4) Push the 'Strike' button of the ultra-violet recorder after it is switched on.

5) Set the paper speed of the ultra-violet recorder.

6) Determine the test conditions for each bay (i.e., deviator stress, confining pressure, the frequency and duration of the load).

7) Set the electrical timing unit at the decided on-load and off-load times. (The sum of on-load and off-load times gives the duration of one cycle, and the on-load time gives the duration of the load.) In this study, the on-load time was 0.25 seconds and the duration of one cycle was 3 seconds. FIGURE A.3 shows a typical load-deformation trace obtained from the ultra-violet recorder for the above conditions.

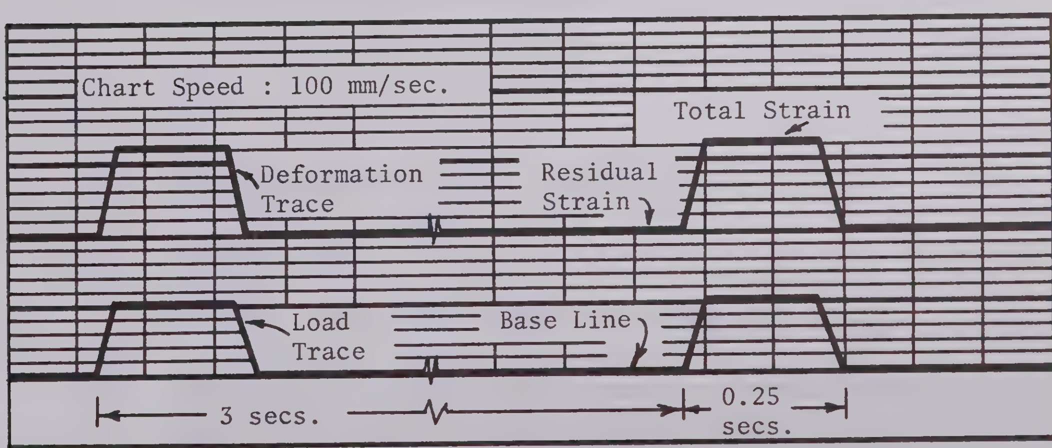


FIGURE A.3 - REPRESENTATION OF STRIP CHART FROM ULTRA-VIOLET RECORDER

a) Setting up Bay No. 1

1) Place a block of wood with a loading cap (dummy sample) in the position for the triaxial cell in bay no. 1.

2) Adjust the loading yoke so that the load cell makes proper contact with the loading cap.

3) The channel selector switch is switched to channel no. 2. (Channel nos. 4 and 6 for bay nos. 2 and 3, respectively.)

4) Switch on the galvanometer switch no. 2.

5) Check the set sensitivity (6 volts) for disturbances.

6) Balance the galvanometer to zero, by adjusting the balance knob no. 2.

7) Switch off the channel selector switch.

8) Bring the marker ray for the load cell to the base line by turning the galvanometer head no. 2 (located in the ultra-violet recorder) with a non-metallic screw driver supplied with the unit.

9) Switch on the bay operation switch for bay no. 1.

10) Gradually open the valve (by turning clockwise), which controls the air pressure for the deviator stress.

11) The magnitude of the load is read from the movement of the marker ray. (Set calibration : 1 Div. = 25 lbs.)

12) After the desired load is reached, lock the air-pressure valve with the lock nut.

13) Switch off the bay operation switch for bay no. 1.

14) Leave the galvanometer switch no. 2 on.

15) Remove the dummy sample from bay no. 1.

16) Place the prepared triaxial cell in bay no. 1.

17) Adjust the loading yoke so that the load cell sits properly on the loading ram.

18) Lightly clamp the LVDT to the clamp bar, which is already clamped to the loading ram of the triaxial cell.

19) Screw in the moving rod of the LVDT (provided with the screw) into the threaded slot in the top cap of the triaxial cell.

20) Switch on the galvanometer switch no. 1. (Channel nos. 3 and 5 for bay nos. 2 and 3, respectively.)

21) Switch on the channel selector switch to channel no. 1.

22) Check the set sensitivity (6 volts) for disturbances.

23) Balance the galvanometer to zero, by loosening the LVDT clamp and moving the LVDT up or down.

24) Clamp the LVDT firmly after the galvanometer is balanced.

25) Switch off the channel selector switch.

26) Bring the marker ray for the LVDT to the base line by turning the galvanometer head no. 1 (located in the ultra-violet recorder) with a <u>non-metallic</u> screw driver supplied with the unit.

27) Leave the galvanometer switch no. 1 on.

28) Set the three-way transducer switch to bay no. 1.

29) Connect the lateral pressure supply line and the pressure recording line for the transducer, to the lateral pressure supply connection and to the pore-pressure measurement connection, respectively, in the base of the triaxial cell.

30) Open the valve in the connection, connecting the cell pressure to the transducer.

31) Read the strain indicator for zero cell pressure.

32) Convert the desired cell pressure to be used, to the strain indicator reading. (Set sensitivity : 1 psi = 33.2 div. of strain indicator for transducer no. 28749.)

33) Add the converted strain indicator reading to the reading for zero cell pressure, and set the strain indicator dial to that value.

34) Slightly open the valve controlling the air pressure for confining pressure (by turning clockwise), and then open the lateral pressure supply connection valve in the base of the triaxial cell. (This is done to avoid water from the triaxial cell coming into the air-pressure line.)

35) Continue increasing the air pressure supply till the meter in the strain indicator is balanced to zero.

36) Lock the air-pressure valve with the lock nut.

37) Set the counter to zero.

38) Adjust the guides on the loading yoke (by turning them on the thread) so that they come within the guide frame.

39) Determine the anticipated maximum deflection the sample is likely to undergo.

40) Adjust the gap between the safety microswitch and the steel bar according to the determination in the previous step.

41) Bay no. 1 is ready for operation.

42) To start operation, switch the paper movement switch in the ultra-violet recorder to 'Drive' and then switch on the bay operation switch for bay no. 1.

b) Setting up Bay Nos. 2 and 3

The procedure for bay no. 1 is repeated for bay no. 2 and bay no. 3.

A.3. Precautions

1) The sensitivity control knobs of the galvanometer and signal conditioner unit should not be touched at all.

2) Once the test is started, the LVDT should not be handled unless the marker ray is about to go off the recording paper and requires resetting. In that case, the reading of the LVDT marker ray should be taken and then the LVDT should be reset so that the marker ray comes to the desired base line. It must be noted that on this new base

line, the value of the last LVDT reading must be added to the reset base line (which for all practical purposes is taken as zero, for the new operation).

3) Adjust the galvanometer heads with a non-metallic (non-magnetic) screw driver supplied with the unit, and not with any metallic screw driver.

4) Never remove the recorder cover without having the recorder turned off because,

   a) The fan is very close to the cover and may be damaged if the cover is removed while it is running.

   b) Light damage to the eye would be severe, if looked directly at the bulb.

5) Dust cover should be placed over the ultra-violet recorder when it is not in use.

6) Always switch off the various power switches in individual units, before disconnecting the main power plug.

7) Precaution should be taken never to apply a negative pressure to the pressure transducer.

8) All electronic equipments and parts functioning electronically must be handled delicately.

A.4. Electrical Connections and Calibration Curves

The remaining pages of this appendix give the schematic diagrams of the electrical connections for the measuring and recording equipment. The calibration curves for the load cells and the pressure transducer are also included.

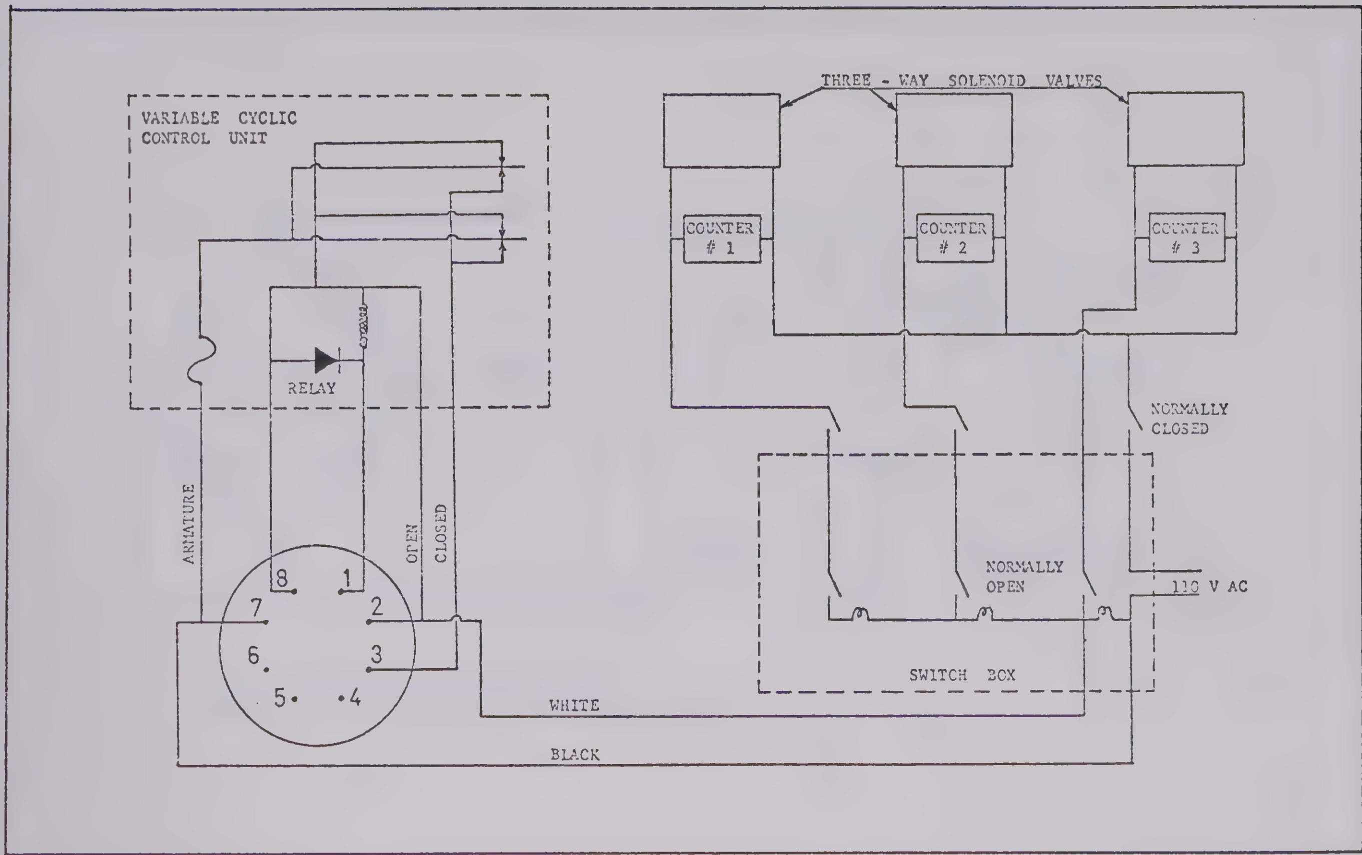
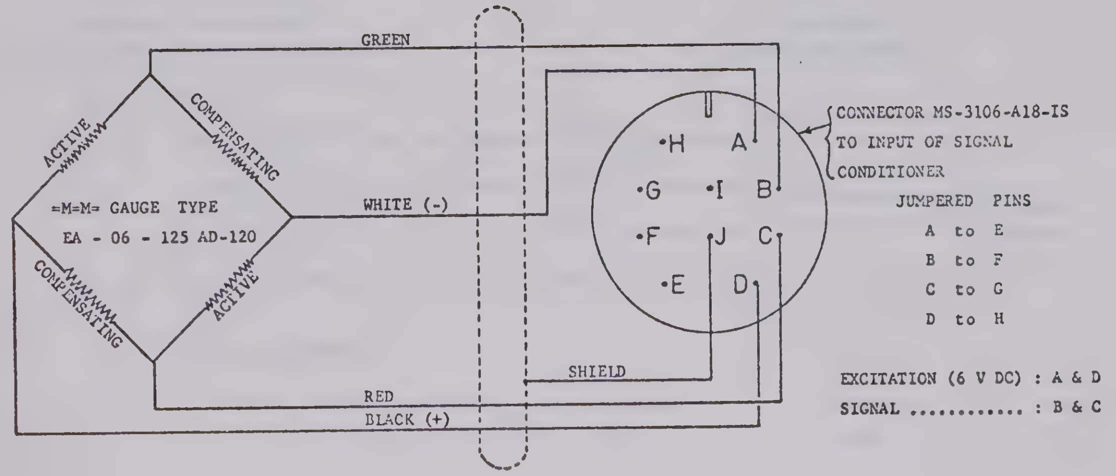
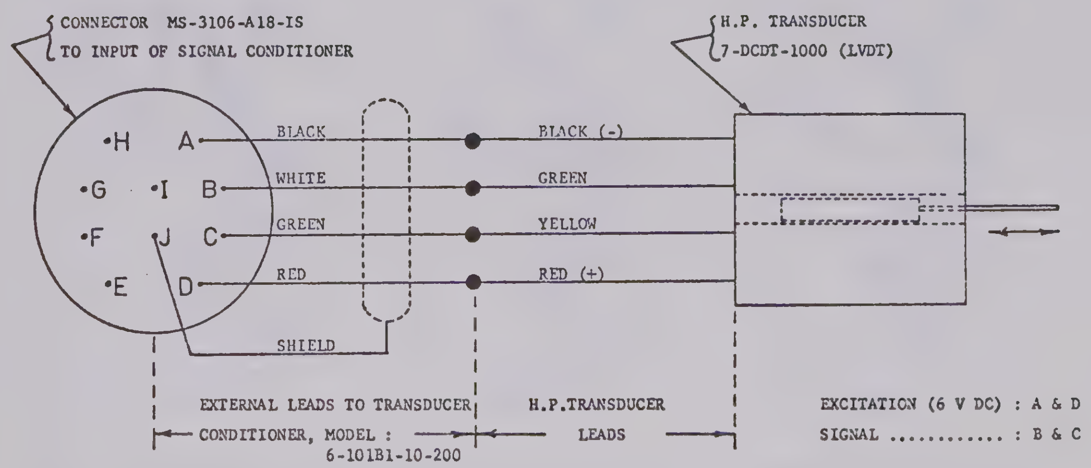


FIGURE A.4 - HOOK-UP FOR VARIABLE CONDITIONER SYSTEM



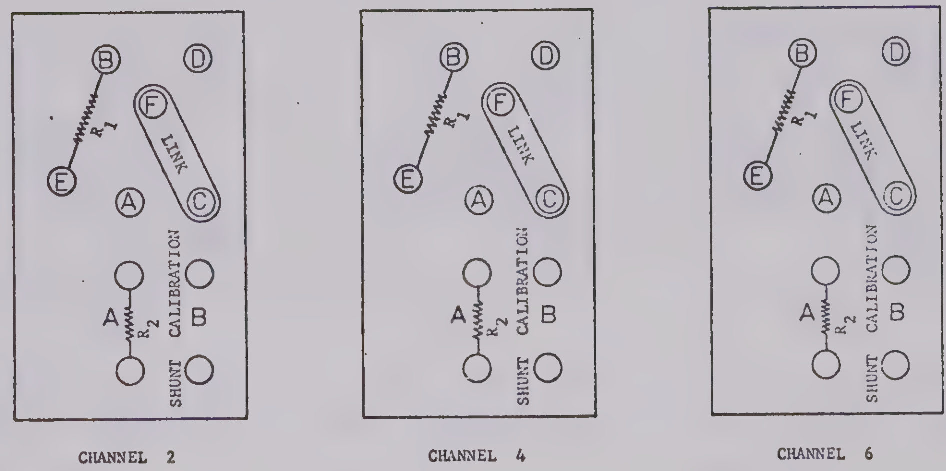
NOTE: All three Load Cells are wired identically.
Connected to inputs 2,4 & 6 of Transducer conditioner.

FIGURE A.5 - HOOK-UP FOR LOAD CELL



NOTE : All three LVDTs are wired identically.
Connected to inputs 1,3 & 5 of Transducer conditioner.

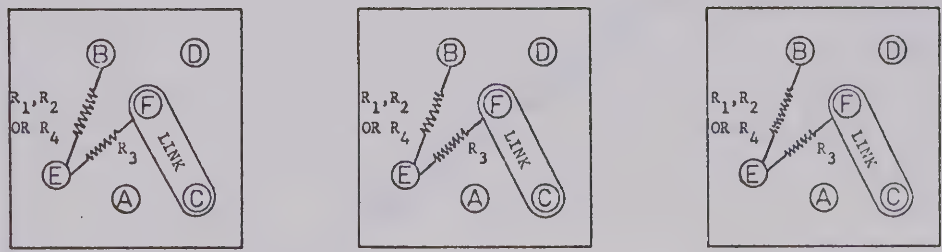
FIGURE A.6 - HOOK-UP FOR LVDT



R_1=153 OHM, 1 DIV.=25 lbs.	R_1=155 OHM, 1 DIV.=25 lbs.	R_1=145 OHM, 1 DIV.=25 lbs.
R_2=43.8K OHM, 75 DIV.=1875 lbs.	R_2=43.6K OHM, 75 DIV.=1875 lbs.	R_2=45.5K OHM, 75 DIV.=1875 lbs.

NOTE : All Resistors are 0.25 W and 1% tolerance

FIGURE A.7 - HOOK-UP FOR LOAD CELL CALIBRATION RESISTORS



CHANNEL 1	CHANNEL 3	CHANNEL 5
R_1=20.7K OHM, 1 DIV.=1.0x10^{-3}in.	R_1=22.0K OHM, 1 DIV.=1.0x10^{-3}in.	R_1=24.8K OHM, 1 DIV.=1.0x10^{-3}in.
R_2=392K OHM, 1 DIV.=1.5x10^{-2}in.	R_2=402K OHM, 1 DIV.=1.5x10^{-2}in.	R_2=392K OHM, 1 DIV.=1.5x10^{-2}in.
R_3=348 OHM.	R_3=348 OHM.	R_3=348 OHM.
R_4=255K OHM, 1 DIV.=1.0x10^{-2}in.	R_4=261K OHM, 1 DIV.=1.0x10^{-2}in.	R_4=301K OHM, 1 DIV.=1.0x10^{-2}in.

NOTE : All Resistors are 0.25 W and 1% tolerance.
Shunt calibration switches do not function for LVDT channels.

FIGURE A.8 - HOOK-UP FOR LVDT CALIBRATION RESISTORS

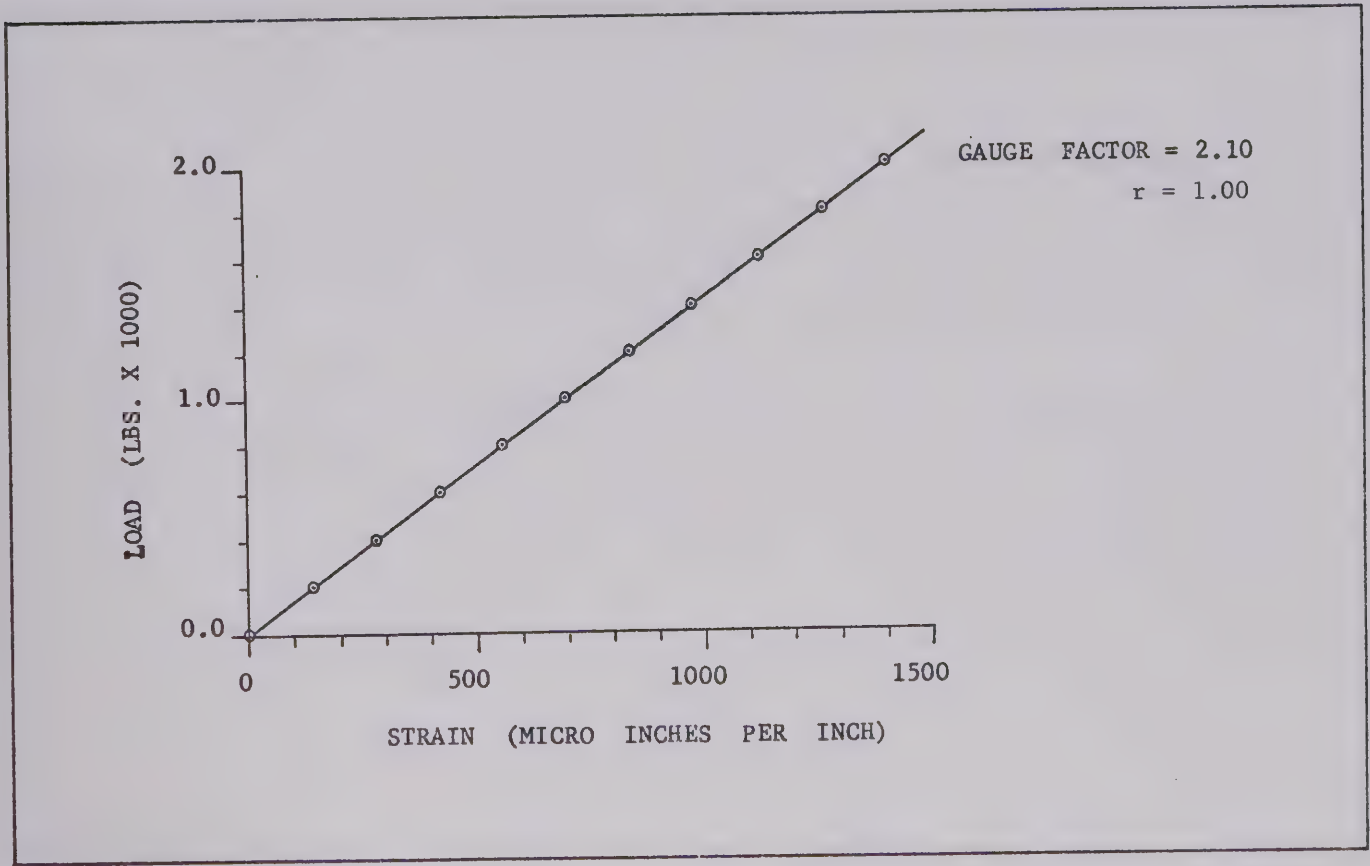


FIGURE A.9 - CALIBRATION CURVE FOR LOAD CELL No. 2

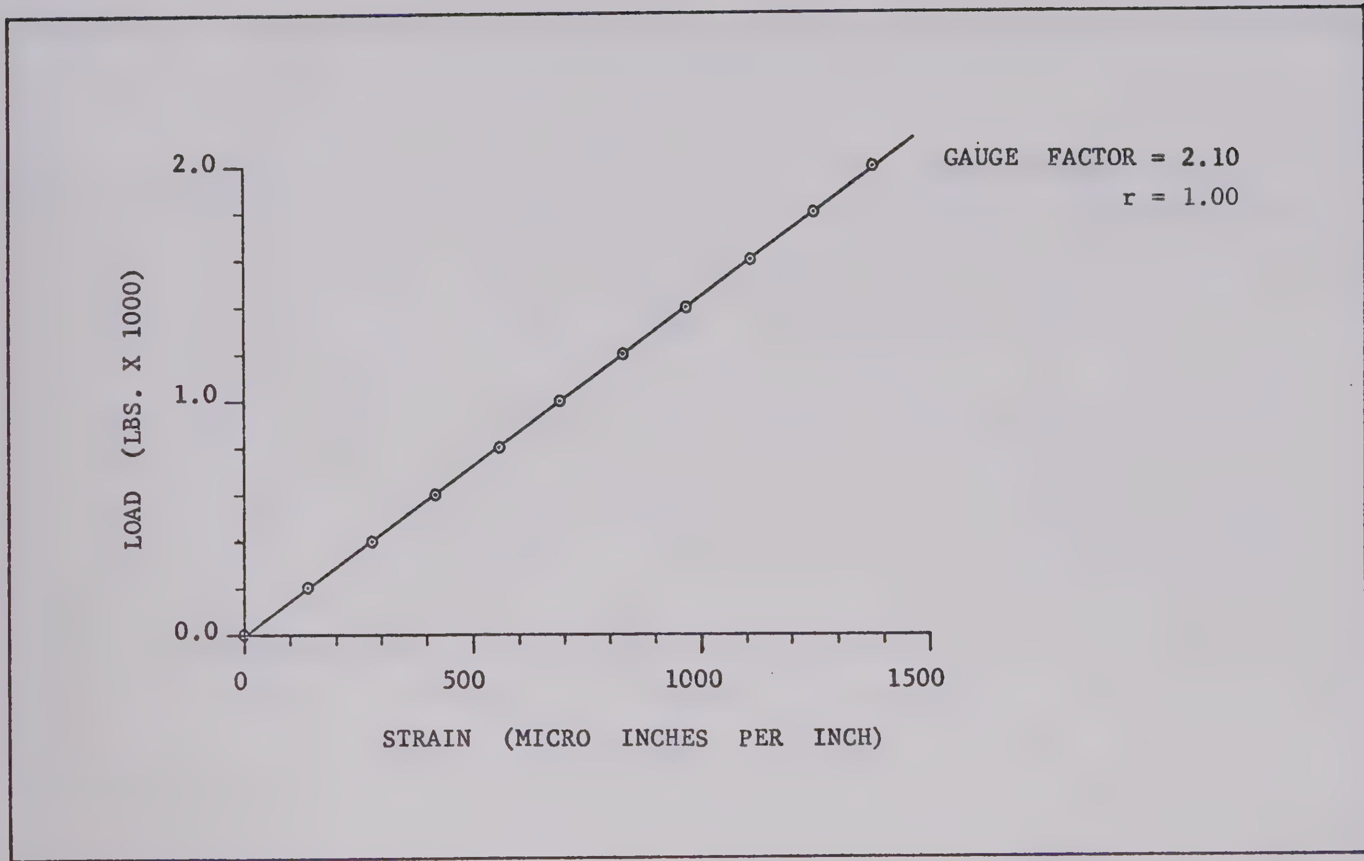


FIGURE A.10 - CALIBRATION CURVE FOR LOAD CELL No. 4

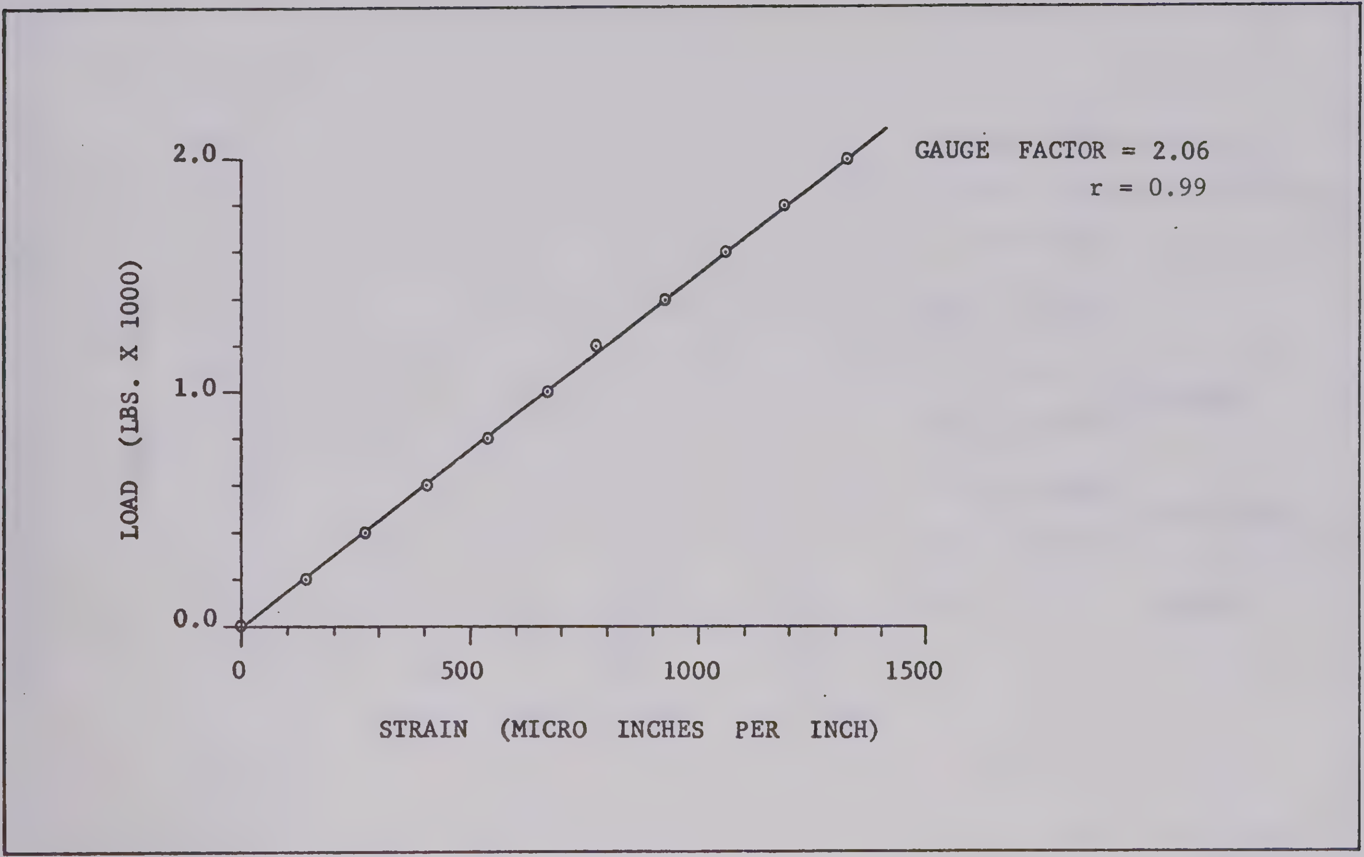


FIGURE A.11 - CALIBRATION CURVE FOR LOAD CELL No. 6

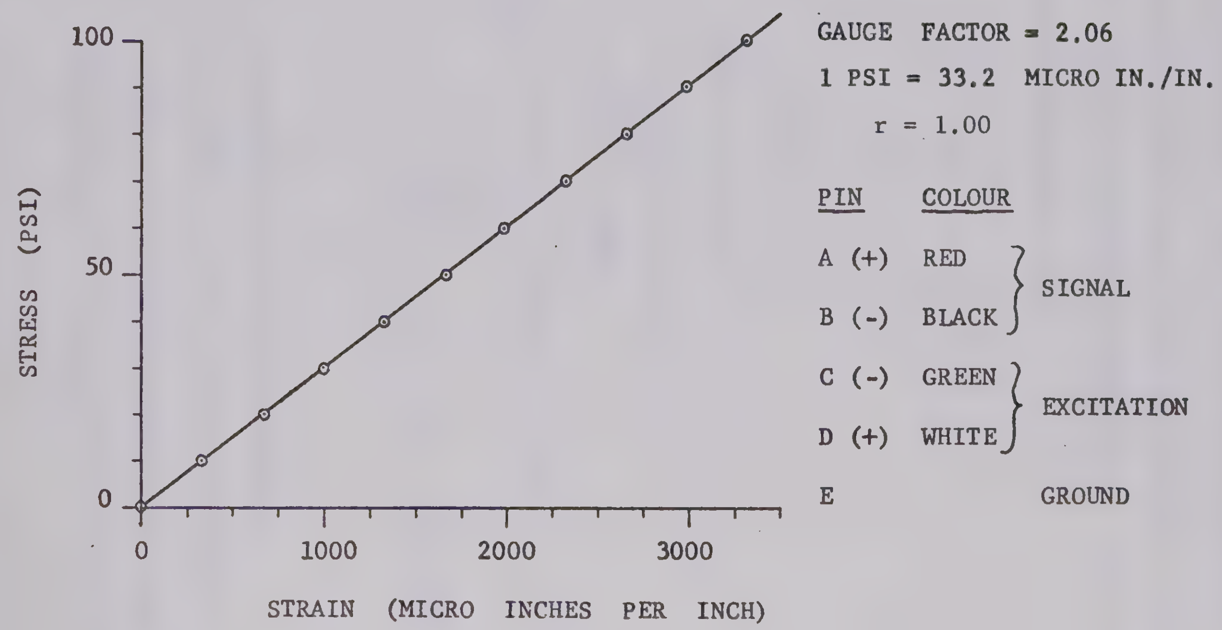


FIGURE A.12 - CALIBRATION CURVE FOR PRESSURE TRANSDUCER No. 28749

A.5. Errors

The uncertainty in the laboratory experimental results were calculated taking into account the uncertainty in each measuring device, by the root sum square method of combination*. The equation for calculating the resilient modulus is

$$M = \frac{\sigma}{\Delta/1} \qquad \text{A.1}$$

in which

M = resilient modulus,

σ = deviator stress,

Δ = recoverable deformation, and

1 = length of sample.

The uncertainty in resilient modulus is given by

$$w_M = \pm \left[\left(\frac{\partial M}{\partial \sigma} \cdot w_\sigma \right)^2 + \left(\frac{\partial M}{\partial 1} \cdot w_1 \right)^2 + \left(\frac{\partial M}{\partial \Delta} \cdot w_\Delta \right)^2 \right]^{1/2} \qquad \text{A.2}$$

in which

w_M = uncertainty in resilient modulus,

w_σ = uncertainty in the measurement of deviator stress,

w_1 = uncertainty in the measurement of length of sample, and

w_Δ = uncertainty in the measurement of recoverable deformation.

---

* J. P. Holman, "Experimental Methods for Engineers", 2nd ed. McGraw-Hill, 1971.

Sample Calculation

Problem parameters are: $\sigma = 8$ psi, $1 = 8$ ins., $\Delta = 0.0075$ ins.,

$w_\sigma = \pm 0.2$ psi, $w_1 = \pm 0.01$ ins.,

and $w_\Delta = \pm 0.5\% = 0.00004$ ins.

From Equation A.1 and problem parameters

$$\frac{\partial M}{\partial \sigma} = \frac{1}{\Delta} = 1066$$

$$\frac{\partial M}{\partial 1} = \frac{\sigma}{\Delta} = 1066$$

$$\frac{\partial M}{\partial \Delta} = -\frac{\sigma \times 1}{\Delta^2} = 1138000$$

Substituting in Equation A.2

$$w_M = \left[(1066 \times 0.2)^2 + (1066 \times 0.01)^2 + (1138000 \times 0.00004)^2\right]^{1/2}$$

$$= \pm 242 \text{ psi}$$

From Equation A.1 and problem parameters

$$M = 8550 \text{ psi}$$

Hence error $= \pm \frac{242}{8550} \times 100 = \pm 2.8\%$

APPENDIX B

AUTOMATIC KNEADING COMPACTOR

B.1. Description and Features

An Electronic - Hydraulic Kneading Compactor (model CS 1000 manufactured by Cox and Sons of Sacramento, California) has been set up in the laboratory at The University of Alberta. Although the compactor is basically designed for requirements specified in California Division of Highways Test Methods 301 and 304, the specimen size normally being 4 inch diameter by 2.5 inch high, it can be used for other compaction procedures and specimen heights up to a maximum of 8 inches.

The apparatus is capable of imparting nearly identical properties to a number of samples which are compacted separately in the machine under the same initial conditions (such as moisture content, etc.).

The tamper foot may be raised or lowered through a maximum height of 9 inches with individual adjustments of : down stroke rate, up stroke rate, up stroke return distance and dwell in down position.

The rotating table is hydraulically actuated and electronically timed to the tamper foot. The table rotation can be varied from 6° to 72° increments for each 360° of table rotation, by adjusting the ten-turn control dial for table rotation.

The automatic feeder assembly is an endless belt type, activated by a hydraulic actuator and electronically timed to the tamper foot.

The loader-conveyor belt feed may be stopped at any time during a load cycle without stopping compaction of the already deposited material. The count will continue but no additional material will be fed from the belt during the interruption.

The return stroke, ram dwell, table rotation and loader stroke can be changed with time to meet the requirements of a compaction procedure. Timing periods are set with precision ten-turn controls and timing of each mode is independent of all other adjustments.

The compaction control mode is divided into three functions, a) Load A, b) Compact, and c) Load B.

The automatic load cycle A permits the specimen to be loaded into the mould in up to 30 equal partitions, with compaction tamps interposed between each incremental addition to the mould. At the conclusion of the loading process, the machine automatically terminates operation.

The automatic load cycle B uniformly loads the specimen into the mould in two volumes of 10 partitions each. After the first half is evenly spread around the mould, the automatic sequence provides 10 compacting tamps of the ram. The second volume is similarly loaded, followed by 10 additional compacting tamps, after which the machine automatically terminates operation.

The compact mode will continuously tamp the specimen until terminated automatically by the predetermining counter or operator.

The Load A and Load B modes are primarily meant for the standard California test methods, but could be used for other purposes as well, if found suitable. Normally the Compact mode is used for different compaction procedures.

FIGURE B.1 shows the essential features of the automatic kneading compactor and it should be referred to for the corresponding alphabetic letters while reading the functions of the various components.

B.1.1. Functions

A Ram Pressure Gauge. Measures the pressure on the specimen directly in pounds per square inch. Total force equals 3.2 foot area multiplied times the gauge reading.

B Predetermining Counter. This counter is used to preset the number of compactive tamps to be applied to the specimen. The counter must be set at zero to begin fabricating a specimen. To preset,

1) Release the locking mechanism of the lid by pressing pushbutton.
2) Open the lid and set figure wheels.
3) Close the lid.
4) The desired number is now visible in the window.
5) The figures must be in alignment.
6) Resetting to zero for repetition or change of pre-selected number is done by pressing the pushbutton.
7) CAUTION: DO NOT ATTEMPT TO PRESET OR RESET COUNTER WITH MACHINE RUNNING.
8) Ram will not operate until the counter is reset.

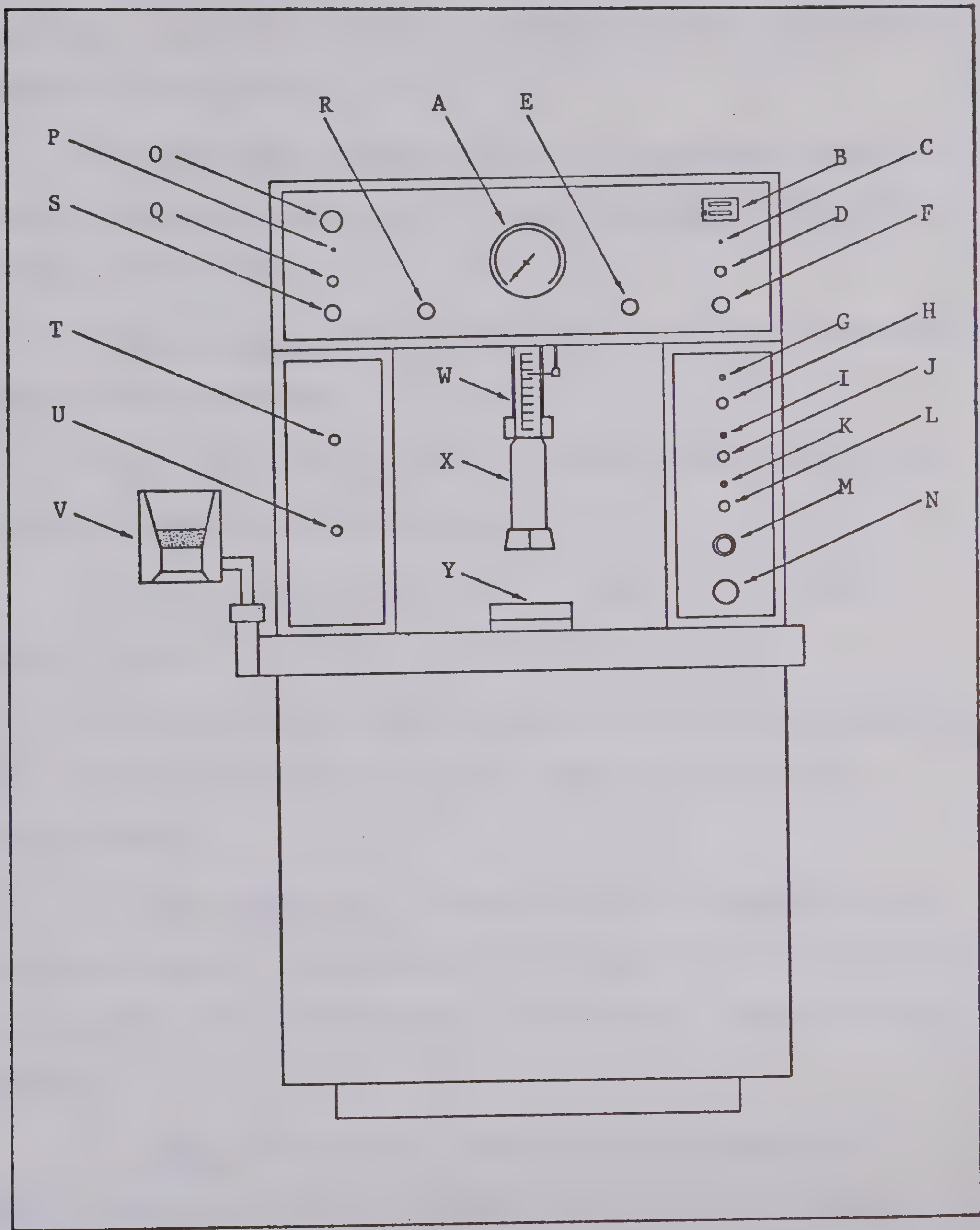


FIGURE B.1 - AUTOMATIC KNEADING COMPACTOR

C <u>Counter Indicating Lamp</u> - Green. An intermittent light that flashes each time the ram advances toward the specimen. Indicates that switch D is in On position.

D <u>Counter Off-On Switch</u>. Must be in On position for the counter to operate automatically. Off position permits ram operation without counter control.

E <u>Return Stroke</u>. This ten-turn dial controls the time interval between strokes of the Ram.

F <u>Ram Dwell</u>. This ten-turn dial controls the amount of time the Ram applies pressure to the specimen.

G <u>Master Indicating Lamp</u> - Red. A light that indicates whenever the master switch is in the On position.

H <u>Master Switch</u>. Controls the electrical power to the machine. Prior to turning off the master switch, <u>ALWAYS</u> place switch L in Ram-Up position.

I <u>Loader Pulse Button</u>. Used to advance the conveyor belt of the loader manually. Load pulses may be interposed by the operator at will by means of this manual button. Loader switch J must be in the On position.

J <u>Loader Off-On Switch</u>. Must be in On position for the control system to activate the conveyor belt.

K <u>Reset Button</u>. Initiates the start of all control modes.

Example: Place switch L in Compact, switch M in any desired mode, and push reset button.

L Ram-Up - Compact Switch. Ram-up position retracts the ram. For SAFETY always use this position when placing hands under the Ram, and before turning off the master switch.

M Control Mode. This control is divided into three functions : Load A, Compact, and Load B. To initiate any of the above modes, place switch L in Compact position and push reset button K.

N Ram Pressure. This knob is used to control the amount of compactive pressure applied to the specimen in pounds per square inch. Turning this knob clockwise will increase the pressure and turning the knob counterclockwise will decrease the pressure.

O Heater. This is the tamper foot heat control for Bituminous Mix specimens. Turn clockwise to increase temperature.

P Heater Indicating Lamp - Amber. This light indicates when the heater is on.

Q Heater Off-On Switch.

R Table Rotation. This ten-turn dial controls the amount of movement of the table between tamps of the Ram.

S Loader Stroke. This ten-turn dial is used to control the length of movement of the conveyor in the loader trough.

T Down Rate (Ram velocity). This knob is used to control the downward velocity of the Ram. Turn clockwise to decrease, counter-clockwise to increase rate.

U Up Rate (Ram velocity). This knob is used to control the upward velocity of the Ram. Turn clockwise to decrease, counterclockwise to increase rate.

V Automatic Conveyor. This device is preset by electronic controls to load in the proper sequence.

Range of belt movement : 0.12 to 3.00 inches per pulse.
Capacity of Conveyor Belt : 1,500 grams.

W Height Indicator Device. This device is not used to actually measure the height of a specimen, but rather to give the operator an approximate idea of the specimen height so that he can be as close as possible to the proper height with the first specimen.

X Ram. The ram transmits the hydraulic pressure of the system to the specimen.

Y Table. A rotating platen upon which the specimen is compacted. This table rotates when the ram is retracting after having applied its compactive force.

To change setting of the ten-turn dial controls E, F, R and S,

1) Release dial lock by pushing counterclockwise.
2) Choose desired number setting.
3) Reset dial lock.

B.2. Operational Procedure

1) Decide on the compaction procedure.
2) Switch on the Master switch (H), and allow the machine to warm up for about 5 minutes.

3) Decide on the settings for Return stroke, Ram dwell, Table rotation, and Loader stroke and set the respective ten-turn dials accordingly.

4) Up rate and Down rate settings for the standard California test methods are adequate for normal use. If a change is desired, they should be set accordingly.

5) Set the mould on the Table (Y).

6) If the mould is to be loaded by conveyor belt feed, place material on the conveyor belt and spread it to a uniform level. Swing the conveyor assembly to feeding position and switch on the loader switch (J).

7) If the mould is to be loaded manually, place the material in the mould and spread it out evenly. Step 6 is omitted for this case.

8) Select the Control mode (M) to one of the three functions, as desired. Load A and Load B cycles function automatically for feeding and compacting, as explained earlier.

9) If the mode selected is Compact and the number of tamps is to be controlled by the predetermining counter, set the desired number of tamps in the predetermining counter (B) and switch on the counter switch.

10) Place Ram-up-Compact switch (L) in Compact position.

11) Press the Reset button (K), which starts the compaction and all control modes.

12) The pressure applied by the tamper foot is read in Ram Pressure Gauge (A). The Ram Pressure knob (N) is manipulated till the desired foot pressure is reached.

13) After completion of the cycle the Ram retracts and machine terminates operation, the Ram-up-Compact switch (L) should be placed in the Ram-up position.

14) If another layer of material is to be added manually and compacted, steps 9, 10, 11, and 13 are repeated after the material is placed in the mould.

15) After the sample has been fabricated and the machine is no longer required for operation, place Ram-up-Compact switch (L) in Ram-up position and switch off all the switches, the Master switch (H) being switched off last.

B.3. Procedure for Fabricating 4 inch Diameter x 8 inch High Specimens

The procedure for fabricating 4 inch diameter x 8 inch high samples was different from that of smaller samples. The normal working of the compactor was restricted due to the large sample height (8 inches). The loader-conveyor belt feed could not be used. A clearance of the cross-arm of the Ram above the top of the mould was only obtained after a 1.5 inch layer of compacted material was inside the mould. It was evident from this difficulty that the sample would have to be compacted in five layers or less, to have the machine working properly.

After several trials it was decided that the material required for preparing one sample be weighed into 5 equal parts. Each part was fed manually into the mould and given 25 tamps of the tamper foot.

During the trials, it was observed that the foot pressure greatly influenced the foot penetration when the moisture content of the soil was wet of optimum moisture content. Hence different foot pressures were used for calibration, depending on the moisture content of the soil, and the trial results are summarized in TABLE B-1.

A series of compaction tests were also run with a different soil at various water contents, for which the ASTM D698-70 Test Curve was available. The mould used was 4 inches in diameter and 4.5 inches high, similar to the one specified for the Standard ASTM D698-70 Test. Samples were compacted in three layers with the machine settings indicated in column (2) of TABLE B-1. The results obtained were compared with those obtained from the Standard ASTM D698-70 Test, and are shown in FIGURE B.2.

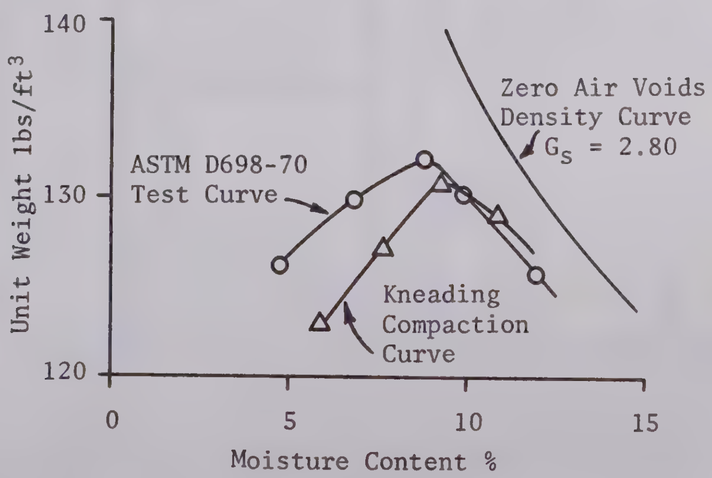


FIGURE B.2 - COMPARISON BETWEEN ASTM D698-70 AND KNEADING COMPACTION TESTS

TABLE B-1

SUMMARY OF TRIAL COMPACTION TESTS FOR FABRICATING
4 INCH DIAMETER BY 8 INCH HIGH SPECIMENS, USING THE KNEADING COMPACTOR

Functions	Soils at OMC or dry of OMC (1)	Soils wet of OMC (2)	Standard California Calibration as supplied by the manufacturer (3)
Foot Pressure (A)	150 psi	100 psi	-
Predetermining Counter (B)	25	25	-
Loader Stroke (S)	Idle	Idle	-
Table Rotation (R)	100	100	-
Return Stroke (E)	140	140	130
Ram Dwell (F)	150	150	020
Down Rate (T)	3.5 turns CCW	3.5 turns CCW	3.5 turns CCW
Up Rate (U)	Locked	Locked	Locked
Dry density obtained by the kneading compactor with the above settings.	112.3 pcf. at 15.1 % moisture content.	110.1 pcf. at 18.2 % moisture content.	-
Dry density obtained by the standard ASTM D 698 - 70.	112.2 pcf. at 15.2 % moisture content.	109.8 pcf. at 18.0 % moisture content.	-
Remarks	Sample was compacted in 5 layers. Foot penetration was low.	Sample was compacted in 5 layers. Foot penetration was 0.25 inches. After the final layer was compacted the foot pressure was reduced to 50 psi and without altering the other settings the sample was subjected to another cycle of compaction.	-

NOTE : CCW - Counterclockwise
OMC - Optimum Moisture Content

B.4. Recommended Test Procedure for Obtaining Standard ASTM D698-70 Densities in 4 inch Diameter by 8 inch High Specimens

The specimen is fabricated in 5 layers with 25 tamps per layer and machine settings set at,

Predetermining Counter	:	25
Loader Stroke	:	Idle
Table Rotation	:	100
Return Stroke	:	140
Ram Dwell	:	150
Down Rate	:	3.5 turns CCW
Up Rate	:	Locked
Foot Pressure	:	Variable depending on the moisture content of the soil. (150 psi at OMC and 100 psi at about 3% wet of OMC).

APPENDIX C

WANG 720 C COMPUTER PROGRAM FOR PROCESSING REPEATED LOADING TRIAXIAL TEST DATA

C.1. Abstract

The program computes the total, residual, and resilient strain in percentile form and the resilient modulus in psi for a particular number of load repetition, and prints the computed results.

C.2. Program Initiation

The program is in the first block in Side 2 of M_R Program-Tape. In case the M_R Program-Tape is not available, the listing of the program given in TABLE C-1 should be keyed into the Wang 720 C Computer and the program recorded in a tape. Program Loading Steps;

1) Prime.

2) Load Program (Block 1 in Side 2 of M_R Program-Tape).

3) Verify Program 3159.

Details are given in section C.4

C.3. Program Description

Usually the total strain, residual strain, resilient strain and the resilient modulus are plotted against the logarithm of the number of load repetitions, and this program computes these values and prints them in a format from which it is fairly easy to plot these graphs. The number of load repetitions is programmed in a logarithmic scale such that the value is automatically incremented to the next number of repetition and is displayed in the y-register after the machine

completes the computation of the output parameters for a particular number of load repetition.

The input for the program are the sample number, the deviator stress, the confining pressure, the LVDT sensitivity, the sample length, the total strain and the residual strain. The LVDT sensitivity is in the form of one division in the strip chart representing a certain length (in inches). As such, the total and residual strains from the strip chart are read in the form of number of divisions and are the input parameters for the program. It is from all these inputs that the program computes the respective results. A representation of the strip chart from the ultra-violet recorder is shown in FIGURE A.3 in APPENDIX A.

C.4. Operating Procedure

1) Load the program tape, depress REWIND, depress TAPE READY, depress RUN, PRIME, LOAD PROGRAM.

2) PRIME, VERIFY PROGRAM; x-register should read 3159.

3) Printer ON, AUTO.

4) PRIME; key special function 00 01

   Printer will respond with :

   ....

5) Display : 1 - Y
   2 - X

   Enter data: First part of sample number in y-register,
   Second part of sample number in x-register.

6) Key <u>GO</u>

Printer will respond with :

SAMPLE NO.L Y/X

7) Display : 3 - Y
4 - X

Enter data: σ_d in y-register,
σ_3 in x-register.

8) Key <u>GO</u>

Printer will respond with :

```
.................d = σdpsi......3 = σ3psi......
NO.OF..............STRAIN %..........  MR
..REP....TOTAL...RESIDUAL..RESILIENT...psi.
```

Note: d and 3 must be prefixed with σ, and since the printer does not have that character it must be written later.

9) Display : 5 - Y
6 - X

Enter data: LVDT sensitivity in inches in y-register.
Length of sample in inches in x-register.

10) Key <u>GO</u>

Printer : Idle.

11) Display : 1 - Y (displays the number of repetition)
7 - X

Enter data: Total strain reading in x-register
(number of divisions in strip chart).

12) Key GO

Printer : Idle.

13) Display : 1 - Y (displays the number of repetition)
8 - X

Enter data: Residual strain reading in x-register (number of divisions in strip chart).

14) Key GO

Printer : Will print the calculated total strain, residual strain, resilient strain, and M_R corresponding to the number of repetition of 1. See TABLE C-2 for printer outputs.

15) Display : 2 - Y
7 - X

Repeat steps 11, 12, 13, and 14.

Note: a) If at step 13 it is realized that wrong data was entered for total strain in step 11, press keys SEARCH, 7 and then enter the correct data and proceed to step 12 (the program back steps to step 11).

b) The number of repetition is incremented in a logarithmic fashion after a set of data have been entered and computed. it is incremented in intervals of 1 from 1 to 10, in intervals of 10 from 10 to 100, in intervals of 100 from 100 to 1,000 and so on. If the display in the y-register at step 11 shows a repetition for which there is no data, press keys SEARCH, SEARCH and the number of repetition will be incremented to the next value.

If the number of repetition is different from the normal programmed logarithmic scale, enter the actual number of repetition in y-register before entering the total strain reading in the x-register at step 11.

Example

Display at step 11: 700 - Y
7 - X

Programmed sequence of No. of Rep.	Actual sequence of No. of Rep.
600	600
700	900
800	950
900	1000
1000	

1) Enter 900 in y-register and do steps 11 to 14.

Display : 800 - Y
7 - X (Note that the number of repetition is still in the programmed sequence)

2) Enter 950 in y-register and do steps 11 to 14.

Display : 900 - Y
7 - X

3) Key SEARCH, SEARCH

Display : 1000 - Y
7 - X

Proceed normally from step 11.

c) If at step 15 it is found that the next set of data for total strain and residual strain is the same as those just entered, press keys SEARCH, GO and the printer will print the same results again for the number of repetition

currently displayed in the y-register. However, if the number of repetition displayed in the y-register at this stage is other than what is required, then it should first be changed according to note b).

Example

Data :

Sample No. : L 6/1

σ_d : 16 psi

σ_3 : 3 psi

LVDT sensitivity : 1 div. = 0.001 inches

Length of sample : 6.135 inches

From the strip chart of the ultra-violet recorder :

No. of Rep.	Total Strain Reading (No. of div.)	Residual Strain Reading (No. of div.)
1	13.0	1.0
2	13.3	1.1
3	13.9	1.6
4	14.1	1.8

Do the steps described in section C.4 (operating procedure).

Printer output:

SAMPLE NO.L 6/1

d =16psi 3 = 3psi

NO.OF	STRAIN %			MR
REP	TOTAL	RESIDUAL	RESILIENT	psi
1	.211	.016	.195	8179
2	.216	.017	.198	8045
3	.226	.026	.200	7980
4	.229	.029	.200	7980

TABLE C-1

LISTING OF WANG 720C COMPUTER PROGRAM FOR PROCESSING REPEATED LOADING TRIAXIAL TEST DATA

STEP	CODE	COMMENT OR KEY
0000	04 03	MARK
0001	00 01	0001
0002	04 12	WRITE α
0003	01 08	CR/LF
0004	04 13	END α
0005	04 11	WRITE
0006	15 07	7 SPACES
0007	07 03	3
0008	07 01	1
0009	02 01	SR. 0201
0010	07 02	2
0011	06 04	↑
0012	07 01	1
0013	06 06	()
0014	05 15	STOP
0015	04 11	WRITE
0016	15 14	14 SPACES
0017	04 12	WRITE α
0018	01 01	S
0019	01 12	A
0020	01 15	M
0021	00 05	P
0022	02 09	L
0023	02 05	E
0024	00 02	SPACE
0025	02 06	N
0026	01 09	O
0027	01 06	.
0028	02 09	L
0029	01 02	L. CASE
0030	04 13	END α
0031	06 06	()
0032	04 11	WRITE
0033	02 00	2b.0a
0034	04 12	WRITE α
0035	00 09	/
0036	00 03	BACK SPACE
0037	04 13	END α
0038	06 05	↓
0039	04 11	WRITE
0040	01 00	1b.0a
0041	04 12	WRITE α
0042	01 08	CR/LF
0043	04 13	END α
0044	07 04	4
0045	06 04	↑
0046	07 03	3
0047	06 06	()
0048	05 15	STOP
0049	06 06	()
0050	04 11	WRITE

STEP	CODE	COMMENT OR KEY
0051	15 12	12 SPACES
0052	04 12	WRITE α
0053	01 10	INDEX LF
0054	02 13	d
0055	00 02	SPACE
0056	00 06	-
0057	00 03	BACK SPACE
0058	04 13	END α
0059	04 11	WRITE
0060	02 00	2b.0a
0061	06 06	()
0062	04 12	WRITE α
0063	00 05	p
0064	01 01	s
0065	01 04	i
0066	04 13	END α
0067	04 11	WRITE
0068	15 08	8 SPACES
0069	04 12	WRITE α
0070	03 14	3
0071	00 02	SPACE
0072	00 06	-
0073	04 13	END α
0074	04 11	WRITE
0075	01 00	1b.0a
0076	04 12	WRITE α
0077	00 05	p
0078	01 01	s
0079	01 04	i
0080	01 08	CR/LF
0081	04 13	END α
0082	07 01	1
0083	07 00	0
0084	07 00	0
0085	06 02	x
0086	04 14	STORE Y
0087	00 06	0006
0088	07 04	4
0089	07 05	5
0090	02 01	SR. 0201
0091	04 12	WRITE α
0092	00 02	SPACE
0093	02 06	N
0094	01 09	O
0095	01 06	.
0096	01 09	O
0097	00 14	F
0098	04 13	END α
0099	04 11	WRITE
0100	15 12	12 SPACES

STEP	CODE	COMMENT OR KEY
0101	04 12	WRITE α
0102	01 01	S
0103	02 07	T
0104	01 13	R
0105	01 12	A
0106	01 04	I
0107	02 06	N
0108	00 02	SPACE
0109	03 05	%
0110	04 13	END α
0111	04 11	WRITE
0112	15 14	14 SPACES
0113	04 12	WRITE α
0114	01 15	M
0115	01 13	R
0116	01 08	CR/LF
0117	04 13	END α
0118	04 11	WRITE
0119	15 07	7 SPACES
0120	07 03	3
0121	07 01	1
0122	02 01	SR. 0201
0123	04 12	WRITE α
0124	00 02	SPACE
0125	00 02	SPACE
0126	01 13	R
0127	02 05	E
0128	00 05	P
0129	04 13	END α
0130	04 11	WRITE
0131	15 05	5 SPACES
0132	04 12	WRITE α
0133	02 07	T
0134	01 09	O.
0135	02 07	T
0136	01 12	A
0137	02 09	L
0138	00 02	SPACE
0139	00 02	SPACE
0140	00 02	SPACE
0141	01 13	R
0142	02 05	E
0143	01 01	S
0144	01 04	I
0145	02 13	D
0146	02 14	U
0147	01 12	A
0148	02 09	L
0149	00 02	SPACE
0150	00 02	SPACE

TABLE C-1 (Cont'd.)

STEP	CODE	COMMENT OR KEY
0151	01 13	R
0152	02 05	E
0153	01 01	S
0154	01 04	I
0155	02 09	L
0156	01 04	I
0157	02 05	E
0158	02 06	N
0159	02 07	T
0160	00 02	SPACE
0161	00 02	SPACE
0162	01 02	L. CASE
0163	00 05	p
0164	01 01	s
0165	01 04	i
0166	01 08	CR/LF
0167	04 13	END α
0168	07 04	4
0169	07 05	5
0170	02 01	SR· 0201
0171	07 06	6
0172	06 04	↕
0173	07 05	5
0174	06 06	( )
0175	04 12	WRITE α
0176	01 02	L. CASE
0177	04 13	END α
0178	05 15	STOP
0179	06 03	÷
0180	07 01	1
0181	07 00	0
0182	07 00	0
0183	06 02	x
0184	04 14	STORE Y
0185	00 00	0000
0186	07 00	0
0187	04 04	STORE DIR.
0188	00 01	0001
0189	07 01	1
0190	04 04	STORE DIR.
0191	00 02	0002
0192	07 01	1
0193	07 00	0
0194	04 04	STORE DIR.
0195	00 03	0003
0196	04 08	MARK
0197	04 07	SEARCH
0198	02 00	SR· 0200
0199	04 08	MARK
0200	07 07	7

STEP	CODE	COMMENT OR KEY
0201	05 15	STOP
0202	04 14	STORE Y
0203	00 04	0004
0204	04 15	RECALL Y
0205	00 00	0000
0206	06 02	x
0207	04 14	STORE Y
0208	00 05	0005
0209	04 15	RECALL Y
0210	00 04	0004
0211	07 08	8
0212	06 06	( )
0213	06 06	( )
0214	05 15	STOP
0215	04 15	RECALL Y
0216	00 00	0000
0217	06 02	x
0218	04 14	STORE Y
0219	00 09	0009
0220	04 15	RECALL Y
0221	00 04	0004
0222	04 08	MARK
0223	05 14	GO
0224	06 05	↓
0225	04 15	RECALL Y
0226	00 09	0009
0227	04 11	WRITE
0228	05 00	5b.0a
0229	04 05	RECALL DIR.
0230	00 05	0005
0231	04 11	WRITE
0232	04 03	4b.3a
0233	06 06	( )
0234	04 11	WRITE
0235	05 03	5b.3a
0236	06 01	−
0237	06 05	↓
0238	04 11	WRITE
0239	05 03	5b.3a
0240	04 15	RECALL Y
0241	00 06	0006
0242	06 03	÷
0243	06 05	↓
0244	04 11	WRITE
0245	07 00	7b.0a
0246	04 12	WRITE α
0247	01 08	CR/LF
0248	04 13	END α
0249	04 07	SEARCH
0250	04 07	SEARCH

STEP	CODE	COMMENT OR KEY
0251	04 08	MARK
0252	02 00	0200
0253	04 15	RECALL Y
0254	00 01	0001
0255	04 05	RECALL DIR.
0256	00 02	0002
0257	06 00	+
0258	04 14	STORE Y
0259	00 01	0001
0260	04 05	RECALL DIR.
0261	00 03	0003
0262	05 09	SKIP IF Y=X
0263	07 07	7
0264	05 11	RETURN
0265	04 04	STORE DIR.
0266	00 02	0002
0267	04 12	WRITE α
0268	07 01	1
0269	04 04	STORE DIR.
0270	00 03	0003
0271	07 07	7
0272	05 11	RETURN
0273	05 15	STOP
0274	04 08	MARK
0275	02 01	0201
0276	06 04	↕
0277	07 01	1
0278	04 12	WRITE α
0279	01 03	U· CASE
0280	04 13	END α
0281	04 08	MARK
0282	14 10	1410
0283	04 12	WRITE α
0284	01 06	·
0285	04 13	END α
0286	06 01	−
0287	04 12	WRITE α
0288	04 11	WRITE
0289	04 07	SEARCH
0290	14 10	1410
0291	04 12	WRITE α
0292	01 08	CR/LF
0293	04 13	END α
0294	05 11	RETURN
0295	05 15	STOP
0296	05 12	END

TABLE C-2

WANG 720C PRINTER OUTPUT FOR THE DATA OF FIRST THREE SAMPLES

OF L TEST SERIES

SAMPLE NO·L 1/1 — σ_d = 8psi — σ_3 = 3psi

NO·OF REP	STRAIN % TOTAL	STRAIN % RESIDUAL	STRAIN % RESILIENT	MR psi
1	.062	.000	.062	12800
2	.093	.000	.093	8533
3	.125	.000	.125	6400
4	.125	.000	.125	6400
5	.125	.000	.125	6400
6	.125	.000	.125	6400
7	.125	.000	.125	6400
8	.125	.000	.125	6400
9	.125	.000	.125	6400
10	.125	.000	.125	6400
20	.156	.031	.125	6400
30	.156	.031	.125	6400
40	.187	.062	.125	6400
60	.187	.062	.125	6400
80	.187	.062	.125	6400
100	.187	.062	.125	6400
200	.187	.062	.125	6400
300	.218	.093	.125	6400
400	.218	.125	.093	8533
500	.213	.125	.093	8533
600	.250	.156	.093	8533
700	.250	.156	.093	8533
1000	.250	.156	.093	8533
2000	.562	.375	.187	4266
3000	.562	.468	.093	8533
5000	.562	.468	.093	8533
7000	.593	.500	.093	8533
8000	.593	.500	.093	8533
9000	.593	.500	.093	8533
14000	.593	.500	.093	8533
16000	.593	.500	.093	8533
30000	.593	.500	.093	8533

SAMPLE NO·L 1/2 — σ_d =16psi — σ_3 = 3psi

NO·OF REP	STRAIN % TOTAL	STRAIN % RESIDUAL	STRAIN % RESILIENT	MR psi
10	.187	.000	.187	8533
20	.187	.000	.187	8533
30	.218	.031	.187	8533
40	.218	.031	.187	8533
50	.218	.031	.187	8533
60	.218	.031	.187	8533
70	.218	.031	.187	8533
80	.218	.031	.187	8533
90	.218	.031	.187	8533
100	.218	.031	.187	8533
200	.250	.031	.218	7314
300	.281	.062	.218	7314
400	.312	.093	.218	7314
500	.375	.125	.250	6400
600	.375	.125	.250	6400
700	.375	.125	.250	6400
800	.437	.156	.281	5688
900	.437	.156	.281	5688
1000	.437	.156	.281	5688
2000	.531	.218	.312	5120
3000	.593	.281	.312	5120
4000	.625	.312	.312	5120
7000	.750	.406	.343	4654
8000	.750	.406	.343	4654
9000	.781	.437	.343	4654
10000	.812	.468	.343	4654

SAMPLE NO·L 2/1 — σ_d =14psi — σ_3 = 3psi

NO·OF REP	STRAIN % TOTAL	STRAIN % RESIDUAL	STRAIN % RESILIENT	MR psi
1	.062	.000	.062	22400
2	.250	.062	.187	7466
3	.250	.062	.187	7466
4	.281	.093	.187	7466
5	.281	.093	.187	7466
6	.312	.125	.187	7466
7	.312	.125	.187	7466
8	.312	.125	.187	7466
9	.312	.125	.187	7466
10	.312	.125	.187	7466
20	.343	.156	.187	7466
30	.343	.156	.187	7466
40	.375	.187	.187	7466
50	.375	.187	.187	7466
60	.375	.187	.187	7466
70	.375	.187	.187	7466
80	.375	.187	.187	7466
90	.375	.187	.187	7466
100	.375	.187	.187	7466
200	.437	.250	.187	7466
300	.437	.250	.187	7466
400	.437	.250	.187	7466
500	.437	.250	.187	7466
600	.468	.281	.187	7466
700	.500	.312	.187	7466
800	.500	.312	.187	7466
900	.500	.312	.187	7466
1000	.500	.312	.187	7466
2000	.531	.343	.187	7466
4000	.625	.375	.250	5600
5000	.625	.375	.250	5600
6000	.625	.375	.250	5600
7000	.656	.406	.250	5600
8000	.656	.406	.250	5600
14500	.750	.500	.250	5600
29000	.781	.531	.250	5600

TABLE C-2 (Cont'd.)

NO•OF	SAMPLE NO•L 3/1 σ_d =10psi σ_3 = 3psi			
	STRAIN %			MR
REP	TOTAL	RESIDUAL	RESILIENT	psi
1	.312	.093	.218	4571
2	.312	.093	.218	4571
3	.343	.125	.218	4571
4	.343	.125	.218	4571
5	.343	.125	.218	4571
6	.375	.125	.250	4000
7	.375	.125	.250	4000
8	.375	.125	.250	4000
9	.375	.125	.250	4000
10	.375	.125	.250	4000
20	.437	.187	.250	4000
30	.437	.187	.250	4000
50	.468	.218	.250	4000
60	.468	.218	.250	4000
70	.468	.218	.250	4000
80	.468	.218	.250	4000
100	.500	.250	.250	4000
200	.500	.250	.250	4000
300	.562	.312	.250	4000
400	.562	.312	.250	4000
500	.562	.312	.250	4000
600	.593	.343	.250	4000
700	.593	.343	.250	4000
800	.625	.375	.250	4000
900	.625	.375	.250	4000
1000	.625	.375	.250	4000
2000	.637	.437	.250	4000
4500	.750	.500	.250	4000
6000	.812	.562	.250	4000
7000	.812	.562	.250	4000
8000	.812	.562	.250	4000
15000	.937	.687	.250	4000

NO•OF	SAMPLE NO•L 3/2 σ_d =25psi σ_3 = 3psi			
	STRAIN %			MR
REP	TOTAL	RESIDUAL	RESILIENT	psi
1	1.000	.218	.781	3200
2	1.187	.375	.812	3076
3	1.312	.500	.842	3076
4	1.437	.625	.812	3076
5	1.562	.718	.843	2962
6	1.656	.812	.843	2962
7	1.750	.875	.875	2857
8	1.812	.937	.875	2857
9	1.875	.968	.906	2758
10	1.937	1.062	.875	2857
20	2.375	1.562	.812	3076
30	2.625	1.842	.812	3076
40	2.812	2.000	.812	3076
60	3.062	2.250	.842	3076
70	3.125	2.312	.812	3076
80	3.187	2.375	.812	3076
90	3.250	2.437	.812	3076
100	3.281	2.468	.812	3076
200	3.750	2.937	.812	3076
300	4.031	3.218	.812	3076
400	4.125	3.312	.812	3076
500	4.218	3.406	.812	3076
600	4.281	3.437	.843	2962
700	4.343	3.531	.812	3076
800	4.406	3.593	.812	3076
900	4.468	3.656	.812	3076
1000	4.500	3.687	.812	3076
2000	4.625	3.812	.812	3076
3000	4.750	3.937	.812	3076
4000	4.843	4.031	.812	3076
5000	4.937	4.125	.812	3076
7000	5.187	4.375	.812	3076
8000	5.250	4.437	.812	3076
9000	5.343	4.531	.812	3076
10000	5.375	4.562	.812	3076
26000	5.937	5.125	.812	3076
30000	6.000	5.187	.812	3076

APPENDIX D

STIFFNESS OF ASPHALT MIXTURE BY INDIRECT METHOD

D.1. Stiffness of Mixture - Loading Time Relationship

The procedure used for the determination of stiffness of mixture - loading time relationship for the asphalt concrete used in the construction of Highway 15-A-1, is based on the procedure suggested by McLeod (1969). A sample calculation for determining the relationship at 60°F is included, which constitutes the master curve shown in FIGURE 5.1. The same relationship was determined for other temperatures and using the shift factor concept as described by Finn (1967), these curves were transferred to the master curve. The shift factor - temperature relationship is shown in FIGURE 5.2 in the text.

D.2. Determination of Master Curve and Shift Factor

D.2.1. Master Curve

The recovered properties of asphalt concrete is presented in TABLE III-2 in the text, from which the relevant properties required for the determination of the master curve are:

Penetration at 77°F (25°C)	: 169
Viscosity at 140°F (60°C)	: 572 poises
Percent air voids	: 5.7
Percent voids in mineral aggregate (VMA)	: 16.5
Volume concentration of aggregate (C_v)	: 0.86
Corrected volume concentration of aggregate (C_v')	: 0.84

Procedure: Refer to McLeod (1969) page 172.

Step 1: From recovered properties,

Penetration at 77°F : 169

Viscosity at 140°F : 572 poises.

Step 2: From these values,

Penetration Index : -1.0.

Step 3: For penetration at 77°F = 169

and penetration index = -1.0

Temperature difference obtained = 14°C

Hence Base temperature = 25 + 14 = 39°C.

Step 4: The curve is to be determined for a service temperature of 60°F (15.6°C), which is 23.4°C (39.0 - 15.6 = 23.4) below the Base temperature.

For a loading time of 0.01 seconds, stiffness modulus of asphalt cement = 200 kg/cm^2 = 2.84×10^3 psi.

Step 5: Volume concentration of aggregate,

$$C_v = \frac{100 - VMA}{100 - \text{air voids}} = \frac{100 - 16.5}{100 - 3.0} = 0.86$$

Corrected volume concentration of aggregate according to Van Draat's and Sommer's equation,

$$C_v' = \frac{C_v}{1+\Delta v} = \frac{0.86}{1 + (0.057 - 0.030)} = 0.84$$

Step 6: Stiffness of asphalt mixture at 60°F, 5.3% asphalt content and 5.7% air voids corresponding to a stiffness modulus of asphalt cement at 60°F and loading time of 0.01 seconds = 2.84×10^3 psi, is 300,000 psi.

Similarly, stiffness of the same mixture at the same temperature (60°F) and different loading times were calculated and are tabulated in TABLE D-1.

TABLE D-1

STIFFNESS OF MIXTURE FOR VARIOUS LOADING TIMES AT 60°F

Loading Time secs	Stiffness of Mixture psi
10^{-5}	4.5×10^6
10^{-4}	2.0×10^6
10^{-3}	8.0×10^5
10^{-2}	3.0×10^5
10^{-1}	1.1×10^5
10^0	3.2×10^4
10^1	6.5×10^3
10^2	1.2×10^3
10^3	2.0×10^2

These values were plotted (both in logarithmic scale) to give a stiffness of mixture - loading time relationship, and yielded the curve presented in FIGURE 5.1.

D.2.2. Shift Factor

The whole procedure was repeated for different temperatures and the amount by which the curves were shifted horizontally (termed as shift factor) to overlap on the master curve were found and are tabulated in TABLE D-2.

TABLE D-2

SHIFT FACTORS FOR VARIOUS TEMPERATURES

Temperature °F	Shift factor
70	1.54×10^{-1}
60	1.00×10^{0}
44	6.10×10^{0}
35	2.55×10^{1}

These values were plotted (shift factor in logarithmic scale and temperature in linear scale) to give a temperature - shift factor relationship and yielded the curve presented in FIGURE 5.2.

D.2. Use of the Curves

An example is illustrated on how these curves are used to determine the stiffness of the mixture.

Problem : Determine the stiffness of the mixture at a temperature of 42°F and loading time of 0.1 seconds.

Solution: Determine the shift factor from FIGURE 5.2.

For a temperature of 42°F, Shift factor = 8.0.

Calculate the modified loading time (the loading

time at 60°F for the actual loading time at 42°F)

from the equation :

$$\text{modified loading time} = \frac{\text{Actual loading time}}{\text{Shift Factor}}$$

For actual loading time of 0.1 seconds at 42°F, the modified loading time = $\frac{0.1}{8.0} = 1.25 \times 10^{-2}$ seconds. Enter this loading time in FIGURE 5.1 and find the corresponding stiffness from the curve, which is : 270,000 psi.

The stiffness of the mixture at 42°F and for a loading time of 0.1 seconds is 270,000 psi.

APPENDIX E

CHEVRON COMPUTER PROGRAM

```
CMAIN   ****** MAIN ROUTINE - N-LAYER ELASTIC SYSTEM ******
        DIMENSION  RR(20),ZZ(20),E(5),V(5),HH(4),H(4),AZ(190),A(190,5),
       1  B(190,5), C(190,5),D(190,5),AJ(190),RJ1(190),RJ0(190)
        COMMON RR,ZZ,E,V,HH,H,AZ,A,B,C,D,AJ,RJ1,RJ0
        COMMCN R,Z,AR,NS,N,L,ITN,P,RSZ,RST,RSR,RTR,ROM,RMU,SF
        COMMON CSZ,CST,CSR,CTR,COM,CMU
        DIMENSION TITLE(18), BZ(100), X(5,4,4), SC(4), PM(4,4,4), FM(2,2),
       1 TEST(11)
        COMMON TITLE, PSI, NLINE, NOUTP, NTEST, TEST,
       1    ITN4,    LC, JT, TZZ, PR, PA,    EP, T1P, T1M, T1, T2, T3, T4,
       2 T5, T6, T2P, T2M, WA, BJ1, BJ0, BZ, ZF, SZ1, SZ2, PM, SG1, SG2,
       3 PH, PH2, VK2, VKP2, VK4, VKP4, VKK8, X, SC, FM
C
C       INITIALIZE VARIABLES
        NOUTP=0
          ITN = 46
        ITN4 = ITN*4
     10 READ(5,310,END=62) (TITLE(I),I=1,18)
    310 FORMAT (18A4)
        IOK=0
        ICALL=0
        READ(5,311) WGT,PSI
    311 FORMAT (2F12.0)
        READ(5,312)               NS, (E(I),V(I), I=1,NS)
    312 FORMAT(I2,5(F8.0,F6.0))
        N = NS - 1
        READ(5,313)               (HH(I), I=1,N)
    313 FORMAT (4F6.0)
C       IF (NPUN) 7,7,8
C     8 PUNCH 355
      7 READ(5,301)               IR,(RR(I),I=1,IR)
        READ(5,301)               IZ,(ZZ(I),I=1,IZ)
    301 FORMAT(I6,(11F6.0))
        AR = SQRT (0.31831   *WGT/PSI)
        NLINE = 17+NS
        NPAGE = 1
        WRITE(6,350)(TITLE(I), I = 1,18 ), NPAGE
    350 FORMAT(1H1//1H0,18H****************** ,1X,18A4,1X,18H*************
       2*****  10X, 7H   PAGE I3 )
        WRITE(6,351)                 WGT, PSI, AR, (I,E(I),V(I),HH(I),I=1,N)
    351 FORMAT(1H0, 40X, 26HTHE PROBLEM PARAMETERS ARE/
       2     1H0, 20X, 12HTOTAL LOAD.., 8X, F10.2, 5H  LBS/
       3     1H0, 20X, 15HTIRE PRESSURE.., 5X, F10.2, 5H  PSI/
       4     1H0, 20X, 13HLOAD RADIUS.., 7X, F10.2, 5H  IN./ 1H /
       5     (1H , 20X, 5HLAYER, I3, 14H  HAS MODULUS , F8.0,
       6      18H   POISSONS RATIO , F6.3, 17H   AND THICKNESS , F5.1,
       7      4H IN.))
        WRITE(6,354)                 NS, E(NS), V(NS)
 354    FORMAT(1H ,20X,5HLAYER,I3,14H  HAS MODULUS ,F8.0,
       1      18H   POISSONS RATIO , F6.3, 24H   AND IS SEMI-INFINITE. )
        WRITE(6,352)
    352 FORMAT(1H0,45X,11HS T R E S S,44X,11HS T R A I N/
       1     1H , 20X,60H*************************************************
       2***********  ,6X,  36H************************************  /
       3 5H    R,6X,1HZ,9X,8HVERTICAL,3X,10HTANGENTIAL,7X,6HRADIAL,8X,
       4 5HSHEAR,9X,4HBULK,8X,8HDEFLECT ,7X,6HRADIAL,9X,4HBULK/1H )
    888 TCOM=0.
```

```
C  ** ADJUST LAYER DEPTHS **
      H(1)=HH(1)
      DO 25 I=2,N
   25 H(I)=H(I-1)+HH(I)
      IRT=0
C  ** START ON A NEW R **
  100 IRT=IRT+1
      IF (IRT-IR) 105,105,10
  105 R=RR(IRT)
      DO 31 I =1,IZ
      DO 31 J=1,N
      TZ  = ABS (H(J) - ZZ(I))
      IF(TZ - .0001) 32,32,31
   32 ZZ(I) = -H(J)
   31 CONTINUE
      WRITE(6,355)
      NLINE = NLINE+1
  355 FORMAT(1H )
C  ** CALCULATE THE PARTITION **
      CALL PART
C  ** CALCULATE THE COEFFICIENTS **
      DO 125 I=1,ITN4
      P=AZ(I)
  107   CALL COEE (I)
  109   IF (R) 115,115,110
  110   PR = P*R
        CALL BESSEL (0,PR,Y)
          RJ0(I) = Y
        CALL BESSEL (1,PR,Y)
          RJ1(I) = Y
  115 PA=P*AR
      CALL BESSEL (1,PA,Y)
      AJ(I)=Y
  125 CONTINUE
  195 IZT=0
C  ** START ON A NEW Z **
  200 IZT=IZT+1
      IF(IZT-IZ) 205,205,100
  205 Z=ABS (ZZ(IZT))
      IF ( NLINE - 54 ) 207,206,206
  206 NPAGE = NPAGE + 1
      NLINE = 8
      WRITE(6,350)(TITLE(I), I = 1,18 ), NPAGE
      WRITE(6,352)
  207 CONTINUE
C  ** FIND THE LAYER CONTAINING Z **
      TZZ = 0.0
      DO 210 J1=1,N
      J=NS-J1
      IF(Z-H(J)) 210,215,215
  210 CONTINUE
      L = 1
      GO TO 34
  215 L=J+1
      IF (ZZ(IZT)) 33,34,34
   33 L = J
      TZZ = 1.0
   34 CONTINUE
      CALL CALCIN(IOK,ICALL,IRT,TCOM)
  889 IF (TZZ) 36,36,35
```

```
   35 ZZ(IZT) = -ZZ(IZT)
      IZT = IZT-1
   36 CONTINUE
C     IF (NPUN) 200, 200, 220
C 220 NZP = IZT-1
C     NRP = IRT-1
C     PUNCH 356, CSZ, CST, CSR, CTR, COM, CMU, NZP, NRP, TITLE(1)
C 356 FORMAT(1X,6E10.3,2I2,9X,A6)
      GO TO 200
   62 STOP
      END
      SUBROUTINE CALCIN(IOK,ICALL,IRT,TCOM)
CCALCIN *****SUBROUTINE CALCIN - N-LAYER ELASTIC SYSTEM ******
      DIMENSION  RR(20),ZZ(20),E(5),V(5),HH(4),H(4),AZ(190),A(190,5),
     1  B(190,5), C(190,5),D(190,5),AJ(190),RJ1(190),RJ0(190)
      COMMON RR,ZZ,E,V,HH,H,AZ,A,B,C,D,AJ,RJ1,RJ0
      COMMON R,Z,AR,NS,N,L,ITN,P,RSZ,RST,RSR,RTR,ROM,RMU,SF
      COMMON CSZ,CST,CSR,CTR,COM,CMU
      DIMENSION TITLE(18), BZ(100), X(5,4,4), SC(4), PM(4,4,4), FM(2,2),
     1 TEST(11)
      COMMON TITLE, PSI, NLINE, NOUTP, NTEST, TEST,
     1    ITN4,    LC, JT, TZZ, PR, PA,    EP, T1P, T1M, T1, T2, T3, T4,
     2 T5, T6, T2P, T2M, WA, BJ1, BJ0, BZ, ZP, SZ1, SZ2, PM, SG1, SG2,
     3 PH, PH2, VK2, VKP2, VK4, VKP4, VKK8, X, SC, FM
      DIMENSION W(4)
    1       W(1) = 0.34785
            W(2) = 0.652145
            W(3) = W(2)
            W(4) = W(1)
    2 VL=2.0*V(L)
      EL=(1.0+V(L))/E(L)
      VL1=1.0-VL
      CSZ=0.0
      CST=0.0
      CSR=0.0
      CTR=0.0
      COM=0.0
      CMU=0.0
      NTS1 = NTEST + 1
      ITS = 1
      JT = 0
      ARP = AR
      IF (NOUTP) 4,4,5
    4 ARP = ARP*PSI
    5 CONTINUE
   10 DO 40 I=1,ITN
C     INITIALIZE THE SUB-INTEGRALS
      RSZ=0.0
      RST=0.0
      RSR=0.0
      RTR=0.0
      ROM=0.0
      RMU=0.0
C     COMPUTE THE SUB-INTEGRALS
            K = 4*(I-1)
      DO 30 J=1,4
          J1 = K + J
      P=AZ(J1)
      EP=EXP (P*Z)
      T1=B(J1,L)*EP
```

```
      T2=D(J1,L)/EP
      T1P=T1+T2
      T1M=T1-T2
      T1=(A(J1,L)+B(J1,L)*Z)*EP
      T2=(C(J1,L)+D(J1,L)*Z)/EP
      T2P=P*(T1+T2)
      T2M=P*(T1-T2)
      WA=AJ(J1)*W(J)
      IF (R) 20,20,15
   15 BJ1=RJ1(J1)*P
      BJ0=RJ0(J1)*P
      RSZ=RSZ+WA*P*BJ0*(VL1*T1P-T2M)
      ROM=ROM+WA*EL*BJ0*(2.0*VL1*T1M-T2P)
      RTR=RTR+WA*P*BJ1*(VL*T1M+T2P)
      RMU=RMU+WA*EL*BJ1*(T1P+T2M)
      RSR=RSR+WA*(P*BJ0*((1.0+VL)*T1P+T2M)-BJ1*(T1P+T2M)/R)
      RST=RST+WA*(VL*P*BJ0*T1P+BJ1*(T1P+T2M)/R)
      GO TO 30
C     SPECIAL ROUTINE FOR R = ZERO
   20 PP=P*P
      RSZ=RSZ+WA*PP*(VL1*T1P-T2M)
      ROM=ROM+WA*EL*P*(2.0*VL1*T1M-T2P)
      RST=RST+WA*PP*((VL+0.5)*T1P+0.5*T2M)
      RSR=RST
   30 CONTINUE
C
       SF = (AZ(K+4) - AZ(K+1))/1.7222726
      CSZ=CSZ+RSZ*SF
      CST=CST+RST*SF
      CSR=CSR+RSR*SF
      CTR=CTR+RTR*SF
      COM=CCM+ROM*SF
      CMU=CMU+RMU*SF
          RSZ = 2.0*RSZ*AR*SF
      TESTH = ABS (RSZ)-10.0**(-4)
      IF (ITS-NTS1 ) 31,32,32
   31 CONTINUE
      TEST(ITS) = TESTH
      ITS = ITS+1
      GO TO 40
   32 CONTINUE
      TEST(NTS1) = TESTH
      DO 33 J = 1,NTEST
      IF (TESTH-TEST(J)) 35,36,36
   35 CONTINUE
      TESTH = TEST(J)
   36 CONTINUE
      TEST(J) = TEST(J+1)
   33 CONTINUE
      IF (TESTH) 50,50,40
   40 CONTINUE
      JT = 1
   50 CSZ=CSZ*ARP
      CST=CST*ARP
      CTR=CTR*ARP
      CSR=CSR*ARP
      CCM=CCM*ARP
      CMU=CMU*ARP
      RSTN=(CSR-V(L) *(CST+CSZ))/E(L)
      BSTS = CSZ+CST+CSR
```

```
      BSTN = BSTS * (1.0-2.0*V(L))/E(L)
      IF (TZZ) 72,72,71
   71 Z = -Z
   72 CONTINUE
      WRITE(6,315)                   R,Z,CSZ,CST,CSR,CTR,BSTS,COM,RSTN,BSTN
  315 FORMAT (1H ,F6.2,F7.2,2X,5E13.4,3X,3E13.4)
      NLINE = NLINE + 1
C     IF (JT) 99,99,60
   60 WRITE(6,316)E(NS)
C 316 FORMAT (1H+,126X,4HSLOW)
  316 FORMAT(1H+,124X,F7.0)
      IF(Z.LE.0.00001) TCOM=TCOM+COM
   99 RETURN
      END
      SUBROUTINE PART
CPART   ******SUBROUTINE PART - N-LAYER ELASTIC SYSTEM ******
      DIMENSION  RR(20),ZZ(20),E(5),V(5),HH(4),H(4),AZ(190),A(190,5),
     1  B(190,5), C(190,5),D(190,5),AJ(190),RJ1(190),RJ0(190)
      COMMON RR,ZZ,E,V,HH,H,AZ,A,B,C,D,AJ,RJ1,RJ0
      COMMON R,Z,AR,NS,N,L,ITN,P,RSZ,RST,RSR,RTR,ROM,RMU,SF
      COMMON CSZ,CST,CSR,CTR,COM,CMU
      DIMENSION TITLE(18), BZ(100), X(5,4,4), SC(4), PM(4,4,4), FM(2,2),
     1 TEST(11)
      COMMON TITLE, PSI, NLINE, NOUTP, NTEST, TEST,
     1    ITN4,    LC, JT, TZZ, PR, PA,    EP, T1P, T1M, T1, T2, T3, T4,
     2 T5, T6, T2P, T2M, WA, BJ1, BJ0, BZ, ZF, SZ1, SZ2, PM, SG1, SG2,
     3 PH, PH2, VK2, VKP2, VK4, VKP4, VKK8, X, SC, FM
C          ** COMPUTE ZEROS OF J1(X) AND J0(X). SET UP GAUSS CONSTANTS **
    1 BZ(1) = 0.0
      BZ(2) = 1.0
      BZ(3) = 2.4048
      BZ(4) = 3.8317
      BZ(5) = 5.5201
      BZ(6) = 7.0156
      K = ITN+1
            DO 2 I=7,K,2
             T = I/2
             TD = 4.0*T - 1.0
    2        BZ(I) = 3.1415927*(T - 0.25 + 0.050661/TD
     1              -0.053041/TD**3 + 0.262051/TD**5)
            DO 3 I=8,ITN,2
             T = (I-2)/2
             TD = 4.0*T + 1.0
    3        BZ(I) = 3.1415927*(T + 0.25 - 0.151982/TD
     1              + 0.015399/TD**3 - 0.245270/TD**5)
      G1=0.8611363
      G2=0.3399810
    4 ZF = AR
      NTEST = 2
      IF (R) 8,8,9
    9 CONTINUE
      NTEST = AR/R + .0001
      IF (NTEST) 6,6,5
    6 CONTINUE
      NTEST = R/AR + .0001
      ZF = R
    5 CONTINUE
      NTEST = NTEST + 1
      IF (NTEST-10) 8,8,7
    7 CONTINUE
```

```
      NTEST = 10
    8 CONTINUE
C         ** COMPUTE POINTS FOR LEGENDRE-GAUSS INTEGRATION **
   15 K = 1
       ZF = 2.0*ZF
       SZ2 = 0.0
      DO 28 I=1,ITN
        SZ1 = SZ2
        SZ2 = BZ(I+1)/ZF
           SF = SZ2 - SZ1
           PX = SZ2 + SZ1
      SG1=SF*G1
      SG2=SF*G2
      AZ(K)=PX-SG1
      AZ(K+1)=PX-SG2
      AZ(K+2)=PX+SG2
      AZ(K+3)=PX+SG1
         K = K + 4
   28 CONTINUE
   40 RETURN
      END
      SUBROUTINE COEE (KIN)
CCOEE   ******SUBROUTINE COEE - N-LAYER ELASTIC SYSTEM ******
      DIMENSION  RR(20),ZZ(20),E(5),V(5),HH(4),H(4),AZ(190),A(190,5),
     1  B(190,5), C(190,5),D(190,5),AJ(190),RJ1(190),RJ0(190)
      COMMON RR,ZZ,E,V,HH,H,AZ,A,B,C,D,AJ,RJ1,RJ0
      COMMON R,Z,AR,NS,N,L,ITN,P,RSZ,RST,RSR,RTR,ROM,RMU,SF
      COMMON CSZ,CST,CSR,CTR,COM,CMU
      DIMENSION TITLE(18), BZ(100), X(5,4,4), SC(4), PM(4,4,4), FM(2,2),
     1 TEST(11)
      COMMON TITLE, PSI, NLINE, NOUTP, NTEST, TEST,
     1    ITN4,    LC, JT, TZZ, PR, PA,    EP, T1P, T1M, T1, T2, T3, T4,
     2 T5, T6, T2P, T2M, WA, BJ1, BJ0, BZ, ZF, SZ1, SZ2, PM, SG1, SG2,
     3 PH, PH2, VK2, VKP2, VK4, VKP4, VKK8, X, SC, FM
      DIMENSION  SV1(4,2),CV1(2,1),SV2(4,4),CV2(2,2),SV3(4,8),CV3(2,4),
     1           SV4(4,16),CV4(2,8),T(8),NT(4)
C     COMMON SV1,CV1,SV2,CV2,SV3,CV3,SV4,CV4,T,NT
          LC = KIN
CS-MX          SET UP MATRIX X =DI*MI*KI*K*M*D
C     COMPUTE THE MATRICES X(K)
      DO 10 K=1,N
      T1=E(K)*(1.0+V(K+1))/(E(K+1)*(1.0+V(K)))
      T1M=T1-1.0
      PH=P*H(K;
      PH2=PH*2.0
      VK2=2.0*V(K)
      VKP2=2.0*V(K+1)
      VK4=2.0*VK2
      VKP4=2.0*VKP2
      VKK8=8.0*V(K)*V(K+1)
C
      X(K,1,1)=VK4-3.0-T1
      X(K,2,1)=0.0
      X(K,3,1)=T1M*(PH2-VK4+1.0)
      X(K,4,1)=-2.0*T1M*P
C
      T3=PH2*(VK2-1.0)
      T4=VKK8+1.0-3.0*VKP2
      T5=PH2*(VKP2-1.0)
      T6=VKK8+1.0-3.0*VK2
```

```
C
          X(K,1,2)=(T3+T4-T1*(T5+T6))/P
          X(K,2,2)=T1*(VKP4-3.0)-1.0
          X(K,4,2)=T1M*(1.0-PH2-VKP4)
C
          X(K,3,4)=(T3-T4-T1*(T5-T6))/P
C
          T3=PH2*PH-VKK8+1.0
          T4=PH2*(VK2-VKP2)
C
          X(K,1,4)=(T3+T4+VKP2-T1*(T3+T4+VK2))/P
          X(K,3,2)=    (-T3+T4-VKP2+T1*(T3-T4+VK2))/P
C
          X(K,1,3)=T1M*(1.0-PH2-VK4)
          X(K,2,3)=2.0*T1M*P
          X(K,3,3)=VK4-3.0-T1
          X(K,4,3)=0.0
C
          X(K,2,4)=T1M*(PH2-VKP4+1.0)
          X(K,4,4)=T1*(VKP4-3.0)-1.0
C         K = K
       10 CONTINUE
C         COMPUTE THE PRODUCT MATRICES PM
          SC(N)=4.0*(V(N)-1.0)
          IF (N-2) 13,11,11
       11 DO 12 K1=2,N
          M=NS-K1
          SC(M)=SC(M+1)*4.0*(V(M)-1.0)
       12 CONTINUE
       13 CONTINUE
C
          K = N
          DO 15 I=1,4
          DO 14 J=1,2
       14 SV1(I,J) = X(K,I,J+2)
       15 CONTINUE
          CV1(1,1) = -2.0*P*H(K)
          CV1(2,1) = 0.0
          K = K-1
          IF(K) 50,50,20
C
       20 CONTINUE
          DO 22 J=1,2
          J1 = J+J
          T(1) = SV1(1,J)
          T(2) = SV1(2,J)
          T(3) = SV1(3,J)
          T(4) = SV1(4,J)
          DO 21 I=1,4
          SV2(I,J1-1) = X(K,I,1)*T(1)+X(K,I,2)*T(2)
       21 SV2(I,J1) =    X(K,I,3)*T(3)+X(K,I,4)*T(4)
       22 CONTINUE
          T(1) = CV1(1,1)
          T(2) = -2.0*P*H(K)
          CV2(1,1) = T(1)
          CV2(1,2) = T(2)
          CV2(2,1) = T(1)-T(2)
          CV2(2,2) = 0.0
          K = K-1
          IF (K) 50,50,30
```

```
C
   30 CONTINUE
      DO 34 J=1,4
      J1 = J
      IF (J1-2) 32,32,31
   31 J1 = J1+2
   32 CONTINUE
      T(1) = SV2(1,J)
      T(2) = SV2(2,J)
      T(3) = SV2(3,J)
      T(4) = SV2(4,J)
      DO 33 I=1,4
      SV3(I,J1) = X(K,I,1)*T(1)+X(K,I,2)*T(2)
   33 SV3(I,J1+2) = X(K,I,3)*T(3)+X(K,I,4)*T(4)
   34 CONTINUE
      T(1) = -2.0*P*H(K)
      DO 35 J=1,2
      CV3(1,J) = CV2(1,J)
      CV3(2,J) = CV2(1,J)-T(1)
      CV3(1,J+2) = CV2(2,J)+T(1)
      CV3(2,J+2) = CV2(2,J)
   35 CONTINUE
      K = K-1
      IF (K) 50,50,40
C
   40 CONTINUE
      DO 42 J=1,4
      T(1) = SV3(1,J)
      T(2) = SV3(2,J)
      T(3) = SV3(3,J)
      T(4) = SV3(4,J)
      T(5) = SV3(1,J+4)
      T(6) = SV3(2,J+4)
      T(7) = SV3(3,J+4)
      T(8) = SV3(4,J+4)
      DO 41 I=1,4
      SV4(I,J) = X(K,I,1)*T(1)+X(K,I,2)*T(2)
      SV4(I,J+4) = X(K,I,3)*T(3)+X(K,I,4)*T(4)
      SV4(I,J+8) = X(K,I,1)*T(5)+X(K,I,2)*T(6)
   41 SV4(I,J+12) = X(K,I,3)*T(7)+X(K,I,4)*T(8)
   42 CONTINUE
      T(1) = -2.0*P*H(K)
      DO 43 J=1,4
      CV4(1,J) = CV3(1,J)
      CV4(2,J) = CV3(1,J)-T(1)
      CV4(1,J+4) = CV3(2,J)+T(1)
      CV4(2,J+4) = CV3(2,J)
   43 CONTINUE
C
   50 CONTINUE
      NT(1) = 1
      DO 51 K=2,N
   51 NT(K) = NT(K-1)+NT(K-1)
      DO 60 K=1,N
      K1 = NS-K
      DO 52 I=1,4
      PM(K1,I,1) = 0.0
      PM(K1,I,2) = 0.0
   52 CONTINUE
      I1 = NT(K)
```

```
      DO 80 I=1,I1
      I2 = I+I1
      GO TO (61,62,63,64),K
   61 CONTINUE
      T(3) = CV1(1,I)
      T(4) = CV1(2,I)
      GO TO 65
   62 CONTINUE
      T(3) = CV2(1,I)
      T(4) = CV2(2,I)
      GO TO 65
   63 CONTINUE
      T(3) = CV3(1,I)
      T(4) = CV3(2,I)
      GO TO 65
   64 CONTINUE
      T(3) = CV4(1,I)
      T(4) = CV4(2,I)
   65 CONTINUE
      T(1) = 0.0
      T(2) = 0.0
      IF (T(3)+68.0) 67,66,66
   66 T(1) = EXP (T(3))
   67 IF (T(4)+68.0) 69,68,68
   68 T(2) = EXP (T(4))
   69 CONTINUE
      DO 80 J=1,2
      GO TO (71,72,73,74),K
   71 CONTINUE
      T(3) = SV1(J,I)
      T(4) = SV1(J,I2)
      T(5) = SV1(J+2,I)
      T(6) = SV1(J+2,I2)
      GO TO 75
   72 T(3) = SV2(J,I)
      T(4) = SV2(J,I2)
      T(5) = SV2(J+2,I)
      T(6) = SV2(J+2,I2)
      GO TO 75
   73 T(3) = SV3(J,I)
      T(4) = SV3(J,I2)
      T(5) = SV3(J+2,I)
      T(6) = SV3(J+2,I2)
      GO TO 75
   74 T(3) = SV4(J,I)
      T(4) = SV4(J,I2)
      T(5) = SV4(J+2,I)
      T(6) = SV4(J+2,I2)
   75 CONTINUE
C
      PM(K1,J,1) = PM(K1,J,1)+T(1)*T(3)
      PM(K1,J,2) = PM(K1,J,2)+T(1)*T(4)
      PM(K1,J+2,1) = PM(K1,J+2,1)+T(2)*T(5)
      PM(K1,J+2,2) = PM(K1,J+2,2)+T(2)*T(6)
   80 CONTINUE
C     SOLVE FOR C(NS) AND D(NS)
      V2=2.0*V(1)
      V21=V2-1.0
      DO 90 J=1,2
      PM(1,J)=P*PM(1,1,J)+V2*PM(1,2,J)+P*PM(1,3,J)-V2*PM(1,4,J)
```

```
   90 FM(2,J)=P*PM(1,1,J)+V21*PM(1,2,J)-P*PM(1,3,J)+V21*PM(1,4,J)
      DFAC=SC(1)/((FM(1,1)*FM(2,2)-FM(2,1)*FM(1,2))*P*P)
          A(LC,NS) = 0.0
          B(LC,NS) = 0.0
          C(LC,NS) = -FM(1,2)*DFAC
          D(LC,NS) =  FM(1,1)*DFAC
C     BACKSOLVE FOR THE OTHER A,B,C,D
      DO 91 K1=1,N
      A(LC,K1)=(PM(K1,1,1)*C(LC,NS)+PM(K1,1,2)*D(LC,NS))/SC(K1)
      B(LC,K1)=(PM(K1,2,1)*C(LC,NS)+PM(K1,2,2)*D(LC,NS))/SC(K1)
      C(LC,K1)=(PM(K1,3,1)*C(LC,NS)+PM(K1,3,2)*D(LC,NS))/SC(K1)
   91 D(LC,K1)=(PM(K1,4,1)*C(LC,NS)+PM(K1,4,2)*D(LC,NS))/SC(K1)
      RETURN
      END
      SUBROUTINE BESSEL(NI, XI, Y)
CBESSEL ******SUBROUTINE BESSEL - N-LAYER ELASTIC SYSTEM ******
      DIMENSION PZ(6),QZ(6),P1(6),Q1(6),D(20)
C
C
    1 PZ(1)=1.0
      PZ(2) = -1.125E-4
      PZ(3) = 2.87109E-7
      PZ(4) = -2.3449E-9
      PZ(5) = 3.98068E-11
      PZ(6) = -1.15361E-12
C
      QZ(1) = -5.0E-3
      QZ(2) = 4.6875E-6
      QZ(3) = -2.32559E-8
      QZ(4) = 2.83071E-10
      QZ(5) = -6.39121E-12
      QZ(6) = 2.31247E-13
C
C
      P1(1) = 1.0
      P1(2) =  1.875E-4
      P1(3) = -3.69141E-7
      P1(4) =  2.77132E-9
      P1(5) = -4.51144E-11
      P1(6) =  1.27505E-12
C
      Q1(1) =  1.5E-2
      Q1(2) = -6.5625E-6
      Q1(3) =  2.84238E-8
      Q1(4) = -3.26620E-10
      Q1(5) =  7.14312E-12
      Q1(6) = -2.53271E-13
C
C
      PI = 3.14159
      PI2 = 2.0*PI
C
C
    9 N = NI
      X = XI
      IF (X-7.0) 10,10,160
C
   10 X2=X/2.0
      FAC=-X2*X2
      IF (N) 11,11,14
```

```
   11 C=1.0
      Y=C
      DO 13 I=1,34
      T=I
      C=FAC*C/(T*T)
      TEST=ABS (C) - 10.0**(-8)
      IF (TEST) 17,17,12
   12 Y=Y+C
   13 CONTINUE
   14 C=X2
      Y=C
      DO 16 I=1,34
      T=I
      C=FAC*C/(T*(T+1.0))
      TEST=ABS (C) - 10.0**(-8)
      IF (TEST) 17,17,15
   15 Y=Y+C
   16 CONTINUE
   17 RETURN
  160 IF (N) 161,161,164
C
C
  161 DO 162 I=1,6
      D(I) = PZ(I)
      D(I+10) = QZ(I)
  162 CONTINUE
      GO TO 163
C
  164 DO 165 I=1,6
      D(I) = P1(I)
      D(I+10) = Q1(I)
  165 CONTINUE
  163 CONTINUE
      T1 = 25.0/X
      T2=T1*T1
      P = D(6)*T2+D(5)
      DO 170 I=1,4
      J = 5-I
      P = P*T2+D(J)
  170 CONTINUE
      Q = D(16)*T2+D(15)
      DO 171 I=1,4
      J = 5-I
      Q = Q*T2+D(J+10)
  171 CONTINUE
      Q = Q*T1
C
      T4 = SQRT (X*PI)
      T6 = SIN (X)
      T7 = COS (X)
C
      IF (N) 180,180,185
C
  180 T5 = ((P-Q)*T6 + (P+Q)*T7)/T4
      GO TO 99
  185 T5 = ((P+Q)*T6 - (P-Q)*T7)/T4
   99 Y = T5
      RETURN
      END
```

TYPICAL COMPUTER OUTPUT

****************** TIRE PRESSURE 80 SINGLE WHEEL LOAD = 9000# ****************** PAGE 1

THE PROBLEM PARAMETERS ARE

TOTAL LOAD.. 9000.00 LBS

TIRE PRESSURE.. 80.00 PSI

LOAD RADIUS.. 5.98 IN.

LAYER 1 HAS MODULUS 175000. POISSONS RATIO 0.330 AND THICKNESS 2.0 IN.
LAYER 2 HAS MODULUS 380000. POISSONS RATIO 0.330 AND THICKNESS 6.0 IN.
LAYER 3 HAS MODULUS 10000. POISSONS RATIO 0.400 AND THICKNESS 14.0 IN.
LAYER 4 HAS MODULUS 15000. POISSONS RATIO 0.400 AND THICKNESS 36.0 IN.
LAYER 5 HAS MODULUS 25000. POISSONS RATIO 0.500 AND IS SEMI-INFINITE.

		STRESS					STRAIN			
R	Z	VERTICAL	TANGENTIAL	RADIAL	SHEAR	BULK	DEFLECT	RADIAL	BULK	
0.0	0.0	-0.8000E 02	-0.1062E 03	-0.1062E 03	0.0	-0.2924E 03	0.1664E-01	-0.2558E-03	-0.5681E-03	25000.
0.0	-2.00	-0.7362E 02	-0.6677E 02	-0.6677E 02	0.0	-0.2072E 03	0.1639E-01	-0.1168E-03	-0.4025E-03	25000.
0.0	2.00	-0.7362E 02	-0.1025E 03	-0.1025E 03	0.0	-0.2786E 03	0.1639E-01	-0.1168E-03	-0.2493E-03	25000.
0.0	-8.00	-0.9438E 01	0.1323E 03	0.1323E 03	0.0	0.2551E 03	0.1563E-01	0.2414E-03	0.2282E-03	25000.
0.0	8.00	-0.9438E 01	-0.2269E 01	-0.2269E 01	0.0	-0.1398E 02	0.1563E-01	0.2414E-03	-0.2795E-03	25000.
0.0	-22.00	-0.4359E 01	-0.1295E 01	-0.1295E 01	0.0	-0.6949E 01	0.8297E-02	0.9668E-04	-0.1390E-03	25000.
0.0	22.00	-0.4359E 01	-0.4892E 00	-0.4892E 00	0.0	-0.5338E 01	0.8297E-02	0.9668E-04	-0.7117E-04	25000.
5.00	0.0	-0.7866E 02	-0.1002E 03	-0.9818E 02	0.3083E-03	-0.2771E 03	0.1545E-01	-0.2237E-03	-0.5383E-03	25000.
5.00	-2.00	-0.5786E 02	-0.5235E 02	-0.4892E 02	-0.2575E 02	-0.1591E 03	0.1515E-01	-0.7182E-04	-0.3091E-03	25000.
5.00	2.00	-0.5786E 02	-0.8033E 02	-0.7288E 02	-0.2575E 02	-0.2110E 03	0.1515E-01	-0.7182E-04	-0.1888E-03	25000.
5.00	-8.00	-0.8025E 01	0.1072E 03	0.9070E 02	-0.1443E 01	0.1899E 03	0.1460E-01	0.1526E-03	0.1693E-03	25000.
5.00	8.00	-0.8024E 01	-0.2120E 01	-0.2532E 01	-0.1443E 01	-0.1268E 02	0.1460E-01	0.1526E-03	-0.2533E-03	25000.
5.00	-22.00	-0.4145E 01	-0.1237E 01	-0.1282E 01	-0.4927E 00	-0.6664E 01	0.8100E-02	0.8703E-04	-0.1333E-03	25000.
5.00	22.00	-0.4145E 01	-0.4737E 00	-0.5419E 00	-0.4927E 00	-0.5160E 01	0.8100E-02	0.8703E-04	-0.6880E-04	25000.
10.00	0.0	0.7922E 00	-0.3463E 02	-0.1305E 02	-0.3962E-04	-0.5188E 02	0.1229E-01	-0.3333E-04	-0.1008E-03	25000.
10.00	-2.00	-0.3879E 00	-0.1930E 02	-0.1305E 02	-0.1012E 02	-0.3274E 02	0.1245E-01	-0.3743E-04	-0.6361E-04	25000.
10.00	2.00	-0.3379E 00	-0.4159E 02	-0.2811E 02	-0.1012E 02	-0.7019E 02	0.1245E-01	-0.3743E-04	-0.5297E-04	25000.
10.00	-8.00	-0.5426E 01	0.6224E 02	0.2687E 02	-0.1547E 01	0.8368E 02	0.1235E-01	0.2136E-04	0.7487E-04	25000.
10.00	8.00	-0.5426E 01	-0.1787E 01	-0.2672E 01	-0.1547E 01	-0.9895E 01	0.1235E-01	0.2136E-04	-0.1977E-03	25000.
10.00	-22.00	-0.3572E 01	-0.1084E 01	-0.1237E 01	-0.8337E 00	-0.5893E 01	0.7580E-02	0.6251E-04	-0.1179E-03	25000.
10.00	22.00	-0.3572E 01	-0.4359E 00	-0.6653E 00	-0.8337E 00	-0.4673E 01	0.7580E-02	0.6251E-04	-0.6231E-04	25000.
20.00	0.0	-0.4189E 00	-0.1222E 02	0.3480E 01	-0.1174E-04	-0.9163E 01	0.8050E-02	0.4373E-04	-0.1780E-04	25000.
20.00	-2.00	-0.2627E 00	-0.6711E 01	0.1713E 01	-0.2645E 01	-0.5261E 01	0.8072E-02	0.2294E-04	-0.1022E-04	25000.
20.00	2.00	-0.2627E 00	-0.1442E 02	0.3871E 01	-0.2645E 01	-0.1081E 02	0.8072E-02	0.2294E-04	-0.9675E-05	25000.
20.00	-8.00	-0.2357E 01	0.1934E 02	-0.1012E 02	-0.8201E 00	0.6857E 01	0.8052E-02	-0.4138E-04	0.5135E-05	25000.
20.00	8.00	-0.2357E 01	-0.1034E 01	-0.1770E 01	-0.8201E 00	-0.5161E 01	0.8052E-02	-0.4138E-04	-0.1032E-03	25000.
20.00	-22.00	-0.2175E 01	-0.6856E 00	-0.1033E 01	-0.9771E 00	-0.3893E 01	0.5972E-02	0.1115E-04	-0.7766E-04	25000.
20.00	22.00	-0.2175E 01	-0.3035E 00	-0.8241E 00	-0.9771E 00	-0.3302E 01	0.5972E-02	0.1115E-04	-0.4403E-04	25000.